TRANSACTIONS
OF THE
AMERICAN INSTITUTE
OF
ELECTRICAL ENGINEERS

JANUARY 1 TO JUNE 25, 1912

VOL. XXXI, PART I

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
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1912

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A paper presented at the Pittsburgh Section Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., January 9, 1912.

CENTRAL STATION POWER IN COAL MINES

BY W. A. THOMAS

The increased activity of central station operators in developing markets for power makes this subject of considerable interest to electrical engineers in general and particularly to the engineers of this immediate locality.

The casual observer is doubtless inclined to believe at first thought that, with cheap fuel—particularly of the lower and less salable grades—available at a coal mine, it could not be made an attractive field for the sale of central station power, particularly where the central stations are located in cities where real estate and taxes are comparatively high. The error in such judgment lies in the fact that the coal bin and ash pile are not principal factors in the power problem, but are secondary, even with transportation added to the fuel, to the items of interest and depreciation on investment and load factor on the system.

The writer has not had opportunity to make a close study of load and diversity factors and their relation to power costs, but herein undoubtedly lies the key to the situation as affecting the interest of the central station man and the possible purchaser of central station power for coal mine operation. It is well, therefore, to inquire into the problems of the mining man and how the central station can be of use in their solution.

The principal elements are cost of production, reliability of operation and decreased investment. The primary operations involved in the production of coal are undercutting, transporting and hoisting. The secondary operations, as far as power requirements are concerned, are ventilation, drainage or pumping, operation of tipple and other outside machinery, and a small amount of lighting. Sometimes, however, the question of hoisting is eliminated where drift entries occur, and on the other hand the pumping sometimes becomes one of the primary operations.

It is not the intention of this paper to discuss the relative advantages of electric drive over and above other methods of operation, although as regards cutting, it is interesting to note that the electric coal cutter is estimated as reducing the cost of production of coal from 10 to 12 cents per ton. This operation is one offering a very good load for power as it is fairly continuous throughout the day hours up to 3 or 4 o'clock in the afternoon, and very often forms a fairly desirable night load from 6 o'clock until midnight. It is probable that a more universal electrification of mines will show considerable increase in the use of power for this purpose, as a great many mines which have animal haulage at the present time are using hand methods for undercutting the coal. Statistics show that in one state alone, from 1905 to 1909, there was over 200 per cent increase in the number of electric cutting machines in service, as against something like 30 per cent increase in the number of air cutting machines.

In connection with cutting operations, there are installations where compressed air is in use and will doubtless be perpetuated owing to local conditions or the cost of the installation. It is very probable that in installations of this kind low central station rates for the supply of power will show economy in driving the air compressors with electric motors. This is the practise of the Berwind-White Coal Mining Company, which generates its own power in a central station.

As regards the haulage problem, it is too well known that electricity is superior to any other form of haulage for a discussion of its merits in a paper of this kind. It is recognized that in certain mines the danger of gas explosions is too great to introduce an electric locomotive using trolley for collecting the current. In this case, probably the safest form of mechanical haulage is the compressed air locomotive and the compressor drive again forms a possible market for electric power and makes an extremely desirable load.

The combined problems of cutting and hauling form the nucleus around which an electric installation can be made, and while it is proposed to discuss the question of installation costs a little later, it should be noted that these two problems are usually considered at one time in determining upon such improvements. A number of factors enter into the question of such improvements and where the older mines are not equipped with mechanical haulage, it is necessary in most cases to relay the track with heavier rails to stand the weight of the locomotive, which must necessarily be heavier than the cars in order to offer sufficient drawbar pull to permit of bunching cars into trains and cut down the labor attendant upon the old system.

The original installation for animal haulage in the older mines is usually of narrow gage to permit of easier handling of the cars, and the rails are usually light in weight, as the single loaded cars were the heaviest burden which the tracks had to bear. In most cases these older mines cannot be improved by widening the gage, owing to the haulage roads being " gobbed " up along the sides with waste rock and slate, a certain amount of which is always present in normal mining operations.

After a mine has assumed commercial proportions with any considerable development away from the entry or shaft, it is seldom difficult to demonstrate the possible savings in the use of electric haulage. In fact, it becomes imperative that some form of mechanical haulage be employed, as the capacity of a gangway is limited with animal haulage. In the state of Pennsylvania, unquestionably 75 per cent of the coal is so handled, although in some states it is as low as 45 per cent. These figures have reference to main haulage only and in many cases horses or mules are used to collect the cars to sidings where electric, steam or compressed air locomotives haul them to the point of delivery. There is a large field for gathering locomotives to supplant the animals for this purpose and considerable progress is being made in this direction.

The question of pumping or drainage is oftentimes of great importance, as this load is steady and often heavy. The use of electricity for this operation in all kinds of mines is most advantageous and in nearly all cases, pumping by electricity is much more economical, more flexible and more reliable than steam or compressed air. The use of hot steam pipes in a timbered shaft or gangway is objectionable on account of the rapidity with which it hastens the decay of the timbers.

In shaft mines the most serious problem in the application of electricity is that of hoisting. There seems to be more or less prejudice among coal mining men in this country against the electric hoist, whereas in Europe the principal mines are usually so equipped. Probably one of the most logical reasons for this is a lack of knowledge of their operation, and back of that is the fact that the coal in most American mines is so low in its commercial value that it is hard to justify the capitalization of the electric hoist where it involves the building of a plant to supply power for the hoist, since the combined cost is necessarily more than that of the boiler plant and steam hoist.

With central station energy available, however, we have a different set of conditions and it is my belief that its introduction will open up the hoisting proposition very rapidly. In the past, one of the chief difficulties has been the necessity of converting to direct current for hoisting purposes, but this is no longer true, since the more complete development of the alternating-current hoist motor with the necessary control. The use of straight alternating-current hoist motors up to 500 h.p. capacity is now an accomplished fact.

One important feature of the hoisting problem is the extremely wide variation in the power demand and the influence of the extreme hoisting peaks upon the transmission line, or the entire station if it be a relatively small one. With large stations, however, the influence is relatively less and the use of motors up to 500 h.p. capacity does not prove so objectionable, although sometimes it is found practical to equalize the load if the conditions are such that peak loads are penalized. Various systems have been devised to overcome this fluctuation, among which are the storage battery in the case of the direct-current hoist and the use of the reversing a-c.-d-c. motor-generator set and storage battery in the case of the alternating-current hoist. Investment and maintenance charges are very heavy in both of these systems.

Another system used in connection with the use of alternating-current hoist consists of a synchronous converter floating on the line and connected across the direct-current end of the converter is a shunt-wound motor, on which is mounted a flywheel which acts in the capacity of a mechanical storage battery, operating normally on weakened field and at maximum speed. When the demand from the hoist and other loads combined exceeds a predetermined value, a line relay operates to strengthen the flywheel motor field, bringing its counter e.m.f. up sufficiently to feed back through the converter to supply the excess demand for power. After the passing of the peak, the line relay acts to weaken the motor field and restore energy to the flywheel. This system is an improvement over the use of storage batteries, particularly as to maintenance and efficiency. All of these systems still involve the use of rheostatic control in one of its various forms and the maintenance and repairs of heavy contacts on large hoists.

Probably the most promising equipment, and the one now being most universally installed, is known as the flywheel equalizer system. A complete equipment of this kind consists of a direct-current shunt-wound motor driving the hoist and a motor-generator set, the direct-current generator being connected to the hoist motor and the alternating-current motor to the supply system. Coupled or connected to the motor-generator set is a flywheel, the function of which is to give out energy when the load on the generator exceeds the average value, and to absorb energy when the load falls below the average.

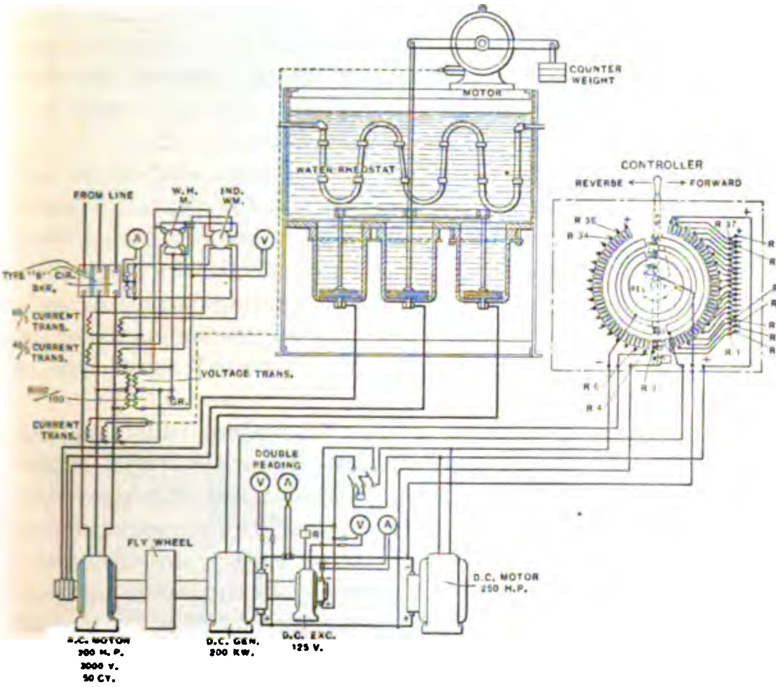


FIG. 1.—DIAGRAM OF CONNECTIONS FOR EQUALIZER SYSTEM FOR 250-H.P. HOIST MOTOR

The hoist motor is separately excited, the excitation not being varied during the operation. The direct-current generator is also separately excited, the armature voltage being controlled by the field strength from full value in one direction down through zero to full value in the opposite direction. To reverse the hoist motor, the field of the generator is reversed, the speed of the hoist motor being practically in proportion to the direct-current generator voltage and being controlled by varying the field strength of the generator, with which any speed desired may be obtained. If, when the motor is running, the field of the generator is weakened so that its voltage falls below the counter e.m.f. of the motor, the latter will act as a generator and return energy to the motor-generator set which, if below full speed, stores energy in the flywheel. This is used instead of a mechanical brake to stop the hoist. It is also used in lowering the men and materials into the mine by pumping back through the motor-generator set to the line, if the energy so derived is sufficient to drive the set slightly above synchronous speed.

In order to equalize the input to the equipment, means are provided for automatically varying the speed of the set. In this connection, a direct-current motor is sometimes used for driving the set and the speed is then varied by regulating the motor field. In a majority of cases, however, the alternating-current motor is used and the speed is varied by regulating the resistance of the alternating-current motor rotor circuit, wound rotor type of motors being used for this purpose.

The regulator is arranged so as to introduce resistance into the circuit when the demand reaches the predetermined value and to keep on adding it as long as the demand stays above this value until the flywheel set is slowed down to the practical limit at which it will pay to use this stored energy, and in reverse manner the regulator automatically cuts out the resistance when the load drops and brings the flywheel set back up to normal speed, restoring energy to the flywheel.

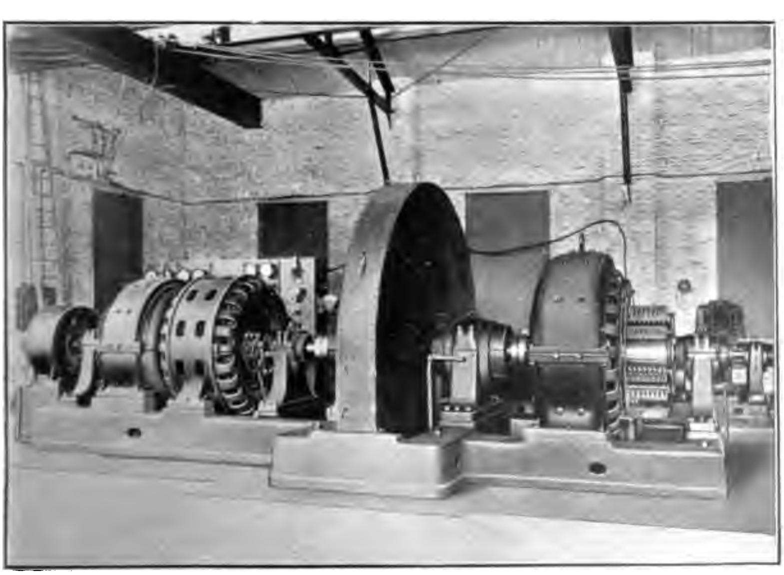
In order to provide for the excitation of the generator and hoist motor, an exciter is usually coupled to the motor-generator set. As the speed of the set is continually varying, a voltage regulator is provided for keeping the voltage of the exciter constant.

For controlling the speed of the motor-generator set, an automatic regulator is used and, as offered by at least one manufacturer, is of the liquid type. This type of regulator has a number of advantages over the arrangement using magnetic switches for cutting the resistance in and out of the rotor circuit, the principal one being greater simplicity and better regulation. One of the most notable installations of this type of hoist is now being installed by the Cleveland Cliffs Iron Company in its Michigan iron mines.

PLATE I
A. I. E. E.
VOL. XXXI, 1912

[THOMAS]

DIRECT-COUPLED ORE HOIST AND GEARED MAN AND MATERIAL HOIST
Cleveland-Cliffs Iron Company, Negaunee, Mich.



[THOMAS]

FLYWHEEL MOTOR-GENERATOR SET FOR HOISTING INSTALLATION
Cleveland-Cliffs Iron Company, Negaunee, Mich.

This equipment covers two hoists, one of 500 h.p. for hoisting ore, and one of 200 h.p. for hoisting men and lowering materials. The operation of the regulator on this installation is very simple, the three phases of the rotor winding being connected to three stationary plates in separate earthenware pots. Above these plates are the movable electrodes which are connected together. The movement of these electrodes is controlled by an induction motor, this motor being supplied with current through series transformers in the line feeding the motor-generator set. The current flowing in the motor is proportional to that in the main line and the torque of the regulator motor varies as the square of this current. The electrodes of the regulator are attached to an arm coupled to the motor shaft and are counterweighted on the other end of this arm beyond the motor shaft. Under normal conditions the counterweight does not quite balance the weight of the electrodes. At the full load current in the main line, the torque of the regulator motor, which tends to separate the electrodes, will be sufficient to bring the whole of the moving parts to a state of equilibrium. Any increase in the current in the main line will cause the torque on the regulator motor to increase rapidly and the electrodes will be separated, thereby introducing resistance into the rotor circuit, thus reducing the speed tendency of the motor-generator set, with the result that the flywheel gives up a portion of its stored energy. If the current in the main line then drops below the value for which the regulator is set, the electrodes will then come closer together and the speed of the set will be increased and energy restored to the flywheel. The regulator in this way tends to maintain the input to the equipment at a constant value.

The electrodes are made of iron and the tank is filled with a solution of carbonate of soda (common washing soda). In the lower portion of the tank, cooling coils can be provided, through which water can be circulated and excessive evaporation of the solution is thereby obviated. The value for which the regulator is set can readily be changed by altering the amount of counterweight, the addition of more weight reducing the current at which the regulator will operate, as the torque required from the motor will be correspondingly less.

The field controller for the direct-current generator is so arranged that the field circuit is never open and in this point in particular the control is ideal. When the controller is in the " off " position, the field is connected across the armature terminals in such a way as to oppose the residual magnetism and any potential generated due to residual magnetism causes current to flow in the field winding, which will tend to build up the field in the opposite direction, thereby killing the residual field. The advantage of this arrangement is that when the hoist is at rest there will be no current flowing. Altogether this system promises much for the solution of the hoisting problem and the equalization of a very intermittent load, so as to make it commercially desirable for central station power supply.

Additional installations of this type of hoisting equipment in this country are the Hecla Mining Company at Burke, Idaho; the Calumet & Arizona Mining Company in Arizona; the Winona Copper Company in Michigan, and some six or seven similar installations in Mexico, notably those in the mines of the El Oro Mining & Railway Co.

It is recognized that this development is most advantageous where fuel costs are high, and consequently the principal installations up to this time have been made in metal mines. This solution of the heavy hoisting problem is nevertheless one of promise and worthy of careful study as applied to coal mining.

In the complete electrification of existing mines having boilers and steam hoists, a suggestion is now being investigated as to the practicability of making such modifications in the steam hoist as are necessary to operate it with compressed air, using one of the boilers as a receiver, and if practical, a re-heater as well, and installing an electrically driven air compressor of such capacity as to work practically all of the time when steady hoisting occurs, the boiler being used to store air while the hoist is out of service, and to supply the excess demand over and above the capacity of the compressor when hoisting. No definite conclusions have been reached as regards either the economy or practicability of this suggestion but it offers a possible simple solution of the perplexing question of what to do with a steam hoist which is sometimes not readily convertible to electric drive.

The ventilation problem is in no way difficult, although we have met with a great deal of prejudice against the use of motors for this purpose as well, but convincing trials have brought mining men to a general use of motors for this application. The Pittsburgh Coal Company is quoted as having established records for continuity of service of electrically driven fans, better than that obtained with steam engines. The load for this purpose is an attractive application from a power standpoint, as the fan is usually required both day and night.

The other secondary operations are considerably varied but comparatively simple in point of application, and combine to make the mine load very attractive to the central station which is so situated as to be able to serve this field. These problems are greatly simplified if the installation is a new one, in which there is no necessity of considering the adaptation of electric drive to existing machinery, and in which we do not have to consider converting an old power house into a substation. The principal market for power, however, for present consideration, is the electrification of the existing mines, the new installations being only incidental to the general situation.

The power consumption in the electrical operation of coal mines varies widely with different local conditions and cannot be accurately predetermined from general data, but requires careful local study, as a wet mine which is not self-draining will require considerable power for pumping purposes, whereas a self-draining mine with water level haulage will be relatively light in its power consumption for both transportation and drainage. The load they get is fairly uniform. In cases of a slope or shaft hoist, additional power is required as against the drift entry.

A number of tests have been made which show as low as 1.22 kw-hr., and as high as 3½ kw-hr. per ton of coal mined with varying conditions. In some cases the service was mixed, using both steam and electricity. In others, rope haulage with steam engines was used. One or two specific cases are illustrated as concrete applications, with the corresponding results. As a general proposition, it is estimated that the power requirements will vary in plants operated entirely by electricity from 1½ to 3½ kw-hr., depending upon the above-mentioned varying conditions, and in the same mine, the requirements will vary with unusual characteristics where a considerable amount of pumping is involved.

MINE NO. 3

Slope-capacity—35,000 tons per month.
Output—15,000 " " "

One 10-h.p. fan
Two 20-h.p. fans
One 20-h.p. pump
One 2½-h.p. pump
Three 10-h.p. pumps

Four 25-h.p. cutting machines.
One 30-h.p. cutting machine.
One 7½-h.p. hoist
One 5-h.p. air compressor
One 5-h.p. shop motor.

Two 80-h.p. locomotives
Two 30-h.p. locomotives
Total—107½ h.p. continuous rating
250 h.p. intermittent rating
Maximum demand = 230 h.p.
1.22 kw-hr. per ton of coal

COMBINED MINING AND COKING PLANT NO. 6

75 Ovens-capacity 5000 tons per month

One	100-kw. motor-generator set
One	100-h.p. alternating-current fan motor
One	15-h.p. direct-current pump motor
One	25-h.p. direct-current coke conveyor and loader
One	5-h.p. direct-current leveler rake
One	25-h.p. direct-current leveler ram
One	40-h.p. direct-current coke pusher
Two	35-h.p. direct-current locomotive motors
One	25-h.p. direct-current larry

Seven months operation 34,000 tons of coke, 110,000 kw-hr. or 3.2 kw-hr. per ton of coke.

When we consider the vast tonnage of coal in the many localities, we begin to appreciate the possibilities of a power market for its production. Among the most prominent installations of the character described are those on the lines of the West Penn Railways Company in the Connellsville, Pa., district, with which many of the local engineers are familiar. The district served in this case involves some of the worst conditions to be met in the way of drainage and hoisting. I feel safe in expressing the opinion, however, that the installations have proved both profitable to the power company and economical to the mining companies.

Considerable activity is evidenced at the present time in other fields, notably the installation now being made in West Virginia by the Appalachian Power Company, which is developing a hydroelectric plant to furnish power in the Pocahontas coal fields. The Pennsylvania Central Power Company, of Altoona, has recently authorized the construction of something like 75 miles (120 km.) of transmission line to cover the Cambria County field.

One extremely advantageous factor in considering this proposition is the fact that with central station energy available, the investment for the small mine is greatly reduced. An isolated plant costing from $12,000 to $15,000 will in many cases be required where a $5,000 substation will do the work. In some cases it has been found advantageous for the central station to put in the substation machinery and operate it on a rental basis, or sell power converted to low voltage or direct current at the busbars. This is the extreme proposition where the mining companies are not sufficiently capitalized to make the improvements and is comparable with the practise of renting simple fixtures to merchants for their lightning contracts, which has also proved advantageous in many cases.

The distribution of the mine load is such as to prove most desirable, as the principal load comes on at, or slightly before, 7 o'clock in the morning and as a rule falls off to a low value between 3 and 4 o'clock in the afternoon, at which time the lighting load picks up during the winter months. It is true that in some cases a comparatively small load comes on again at 6 o'clock and carries through the peak lighting period, but is not of such proportion as to seriously influence the station capacity.

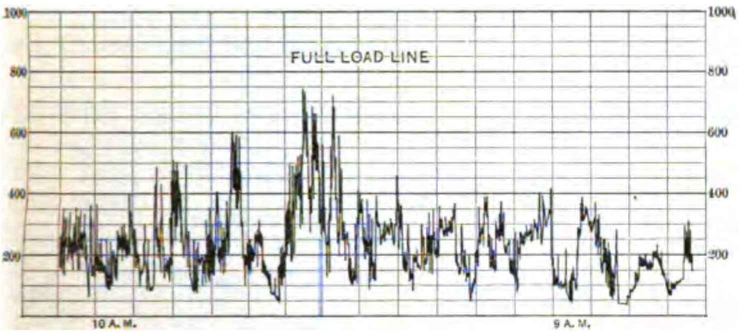


Fig. 2.—Day Load on 800-Ampere Mine Plant

The accompanying charts show the general character of the load and while wide fluctuations occur, they will in the main balance up fairly well where a considerable number of installations are centralized on one plant.

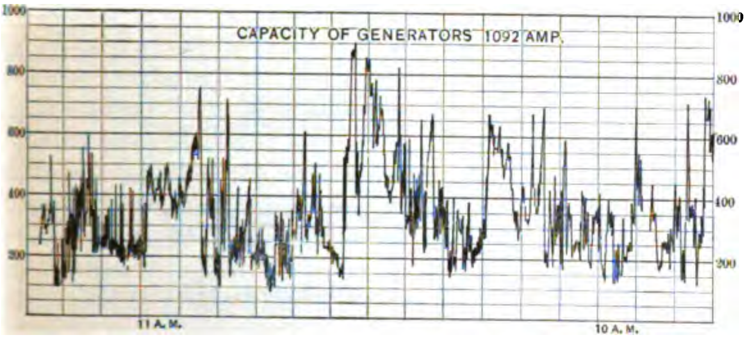


Fig. 3.—Day Load on 1092-Ampere Mine Plant

The question of power contracts calls forth considerable discussion and it is beginning to be recognized that in handling the average mine operator, the same methods cannot always be employed as in handling the industrial plant or the local user of a comparatively small amount of power. The mine operator figures entirely on results and the mine superintendent has ever in mind the cost per ton of producing coal. A serious mistake has been made in one or two cases in putting forth too prominently to the mine operator the value of the central station's readiness to serve. A careful analysis and line of reasoning will doubtless bring the mine operator and central station man together, provided the mine operator realizes that he himself is put to a considerable constant expense if his own plant is shut down, and is not producing energy. Of this feature, however, he often loses sight, owing to the fact that he has taken care of the cost of the plant by an appropriation, and the interest and depreciation are not charged up against the cost of coal.

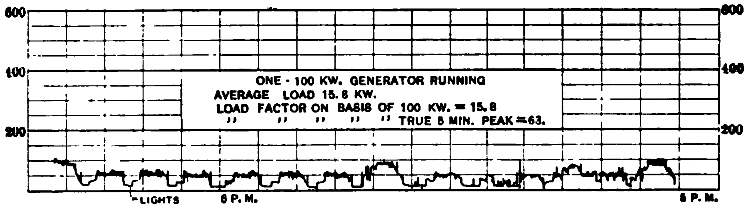


FIG. 4.—EVENING LOAD ON 400-AMPERE MINE PLANT

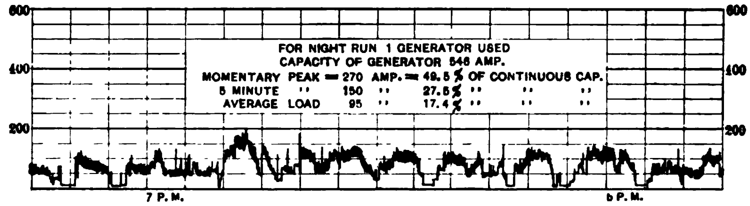


FIG. 5.—EVENING LOAD ON 600-AMPERE MINE PLANT

In talking about the readiness to serve, due consideration should be given to this point and the operator will realize that a certain amount of income is due the central station for the investment necessary to supply power at his demand. On the other hand, the central station solicitor or contract agent should figure carefully the approximate cost that the mine operator must sustain in shutting down his own plant, and it can fairly easily be shown that the minimum charge involved, be it in the form of minimum power consumption or a fixed rate per kilowatt per year, does not much more than offset the real expense represented in the customer's plant when it is standing idle.

A careful analysis of several typical small mining plants shows the average working days per month to be from 15 to 20. It shows the average load factor during an eight-hour day to be slightly over 50 per cent, based on a ratio of average consumption to maximum peak of five minutes duration, and does not take into account the actual capacity of the generators or the momentary swing of the ammeter as indicated in one of the accompanying charts.

Careful tests on four typical plants in Ohio show the following:

Average cost of power	2.485 cents per kw-hr.
Cost for substation equipment, less salvage	0.124 " " " "
Common cost for either source..	0.7 " " " "
Central station rate to balance against present cost	1.661 " " " "
Average power consumption...	47,700 kw-hr.
Average kw-hr. per ton coal...	2.49

As previously inferred, with reference to the discussion of fixed charges or minimum demand, the continuity of power service and its use must be considered. It is evident, therefore, that some form of contract must be considered which will protect the central station against the investment of building the lines and installing sufficient machinery to take care of the maximum demands, if the conditions become abnormal as regards shutting down for a considerable length of time. As regards the relative merits of a fixed charge per kilowatt per year as against a fixed rate per kilowatt-hour with a minimum charge, there are points in favor of both methods. Considering a fixed charge corresponding to the substation capacity, an analysis shows that the approximate cost per horse power installed in the case of the isolated station where it is necessary to keep a fireman at the boiler plant, who can also run the engines where electrical power is used for pumping and other purposes, is approximately $1 per month, based on the total horse power installed in the isolated plant. In establishing a corresponding rate to protect the central station against shut-down, it therefore seems logical to place this at approximately $1.25 per month per kilowatt of substation capacity. This is sometimes reckoned on the total continuous kilowatt capacity of the station, but perhaps a more equitable arrangement as compared with the central station demand is that of taking a maximum five-minute peak or some other form of record which will show a maximum demand of the substation.

In conjunction with this fixed rate of $1.25 per month per kilowatt installed, a relatively lower price per kilowatt-hour is established to protect against the maximum consumption when power is used steadily. This rate, of course, must necessarily vary with local conditions, cases having been known as low as ½ cent per kw-hr. in conjunction with the fixed charge of $1.25 per kilowatt installed.

In the case of the four Ohio plants, the average capacity was 250 kilowatts per station. The average cost per month, say at 1.5 cents per kw-hr., would be $715.50. To arrive at the same result with a fixed charge of $1.25 per kilowatt per month, we would have a fixed cost of $312.50 and a power rate of 0.846 cent per kw-hr.

In studying the accompanying curves, it should be noted that several of these installations served by one power house do not represent nearly so high a kilowatt capacity installed in the central station for this service as proves to be the case with the isolated plant, as, for instance, it is shown that the maximum demand in one or two of the cases does not reach the total station capacity installed. As a rough estimate we figure that the central station capacity for the mine service will not exceed 45 per cent of the total aggregate maximum peaks represented in the various substations served.

A further careful analysis of the character of this load and the fact that a considerable amount of profitable load can be picked up in the small towns adjacent to the mining operations, makes this a particularly attractive field for the supply of central station power, even on the basis of reduced cost of operation to the mine manager.

In the matter of reliability of service, the up-to-date central station has shown results which the isolated station cannot often meet in the way of continuity of service. A secondary consideration which interests the mine operator is the reduction in the number of men required with central station service. We feel safe in predicting that the next five years will see a large percentage of our coal mines operated from public service central station power.

A paper presented at the 267th meeting of the American Institute of Electrical Engineers, New York, January 12, 1912.

SOME NOTES ON ISOLATED PLANTS

BY PERCIVAL R. MOSES

It is perhaps necessary to offer some excuse for presenting to the American Institute of Electrical Engineers some notes on isolated plant design and operation. The general impression is that designing an isolated plant is hardly to be dignified by the term " engineering ". The central station looms so large and the cost of the large central plant so greatly surpasses the largest isolated plant, in the general opinion, as to place questions of design of such stations in a different class from the questions entering into the design of an isolated plant.

Few realize that in reality the design of an isolated plant involves the consideration of as many factors as the design of a central station, and while it is true that there are no isolated plants as large as the plants of the New York public service corporations and similar companies, yet these plants are frequently of many thousand horse power. In the aggregate the isolated plants of a large city far exceed the total horse power of the public utility companies. An engineering directory of the isolated plants in the City of New York (Manhattan) lists a total of 1700 isolated plants. The aggregate boiler horse power of the isolated plants, according to this directory, amounted to over 929,000 h.p., and the aggregate engine h.p. to 669,855. The boiler horse power of the largest central station in New York is listed by the Public Service Commission at 109,000, so the listed boiler horse power in private plants containing engines is over eight times the horse power of the largest central station.

If the list given in the engineering directory is substantially correct, we have nearly a million horse power of boilers in operation in the isolated plants in the City of New York (Borough of Manhattan) alone. My estimate is based on the amount and cost of fuel used in about 50 buildings in New York City, and the engineering pay roll in these buildings. I find that the cost of fuel burned in these buildings varies from $10.00 to $22.00 per boiler h.p. installed. The lower cost is for low-grade fuel in a plant operated on a ten-hour basis, and the highest cost for No. 1 buckwheat coal in an apartment hotel plant of large size, operated twenty-four hours a day. The pay roll varies from $9.00 to $16.00 per boiler h.p. installed. A conservative estimate of the fuel and labor used in the isolated plants in the Borough of Manhattan would be $28.50 per boiler h.p., and on the basis of the list in the engineering directory this would indicate a total expenditure for fuel and labor of over $28,000,000 per year, compared with a total of about $5,000,000 paid for fuel and all the salaries and wages of the largest central station company.

In 14 states of the Eastern Middle and Central groups there were 5,923,302 horse power of boilers and 5,544,888 h.p. of engines listed in isolated plants whereas the census reports for the *whole U. S.* give 3,712,000 h.p. as the total central station engine horse power.

In view of the magnitude of these figures, I believe that I am justified in referring to the isolated plant problem as an "engineering" problem and one worth most careful study and consideration.

PRESENT CONDITIONS OF ISOLATED PLANT DESIGN AND OPERATION

The design of an isolated plant is seldom given the benefit of a sufficient study of the facts. There has not been the wide interchange of data from small isolated plants; operating engineers are usually too busy or too fearful to publish their results. They regard central stations as an enemy ready to shut down their plants, regardless of whether the rate obtained will pay a profit or not. Whether they are justified in this attitude or not is immaterial. The result has been to make it difficult to obtain actual data on the performance of private plants, except in the large mills and similar industrial establishments. Private plants located in buildings adjoining each other use fuel of different grades, one costing perhaps $5 a ton and the other $3. A recent investigation of department stores revealed the fact that some of these stores are burning low-grade fuel costing less than $2 per ton, others are burning No. 2 buckwheat at a cost of $3.25 per ton, and still others are burning pea coal costing $4.10; and one store is burning egg coal, costing in the neighborhood of $6 per ton. It has been equally difficult to get accurate records of loads. Few plants keep regular logs; there are many trustworthy exceptions; and the lack, until recently, of accurate and simple means of measuring the feed water supply to the boiler and the steam delivered, made it practically impossible to obtain continuous records of boiler performance. These conditions were recognized many years ago by the author, and in the plants with which he has had to do, he has endeavored to have regular logs kept, from which reliable data could be obtained on which to base design of subsequent similar plants. A number of load curves from typical buildings derived from such data sheets—log sheets—will be presented a little later, with the hope they may be of use to others designing plants for similar buildings.

Isolated plants vary from a simple plant, consisting of a boiler and an engine, or simpler still, of an oil engine or waterwheel, to the complex equipment of a modern hotel, department store, sugar mill or chocolate factory, containing boilers, gas producers, engines, dynamos, switchboard, motors, refrigerating machinery, heating, evaporating and concentrating apparatus, pumps, elevators, ventilating fans, etc. Perhaps the most perfect example of an isolated plant is the modern transatlantic 1000-foot liner with boiler horse power equaling the horse power of the largest central station, but with the additional complication of moving the ship and its parts.

The isolated plant, properly speaking, is a central plant for the supply of all the heat, light and power requirements of a building, while the usual central station is a central station for the supply of an isolated product.

In discussing isolated plant design it is impossible to confine the investigation to the electric plant alone. It is important to realize fully that the manufacture of electricity is only a small part of the work of the isolated plant. It is one of the processes going on in a building, just the same as refrigeration, heating and the moving of the passengers. The parts are interlinked and interdependent, and with the increase in size and complexity of the modern building and the consolidation of adjoining buildings, this interdependency and interaction becomes more and more important. To emphasize this point, a few of the ways in which the design of each part affects the other, may be noted:

The heating design affects the structural engineering, power plant design, character of the electric lighting used, type of pumps, type of ventilating apparatus.

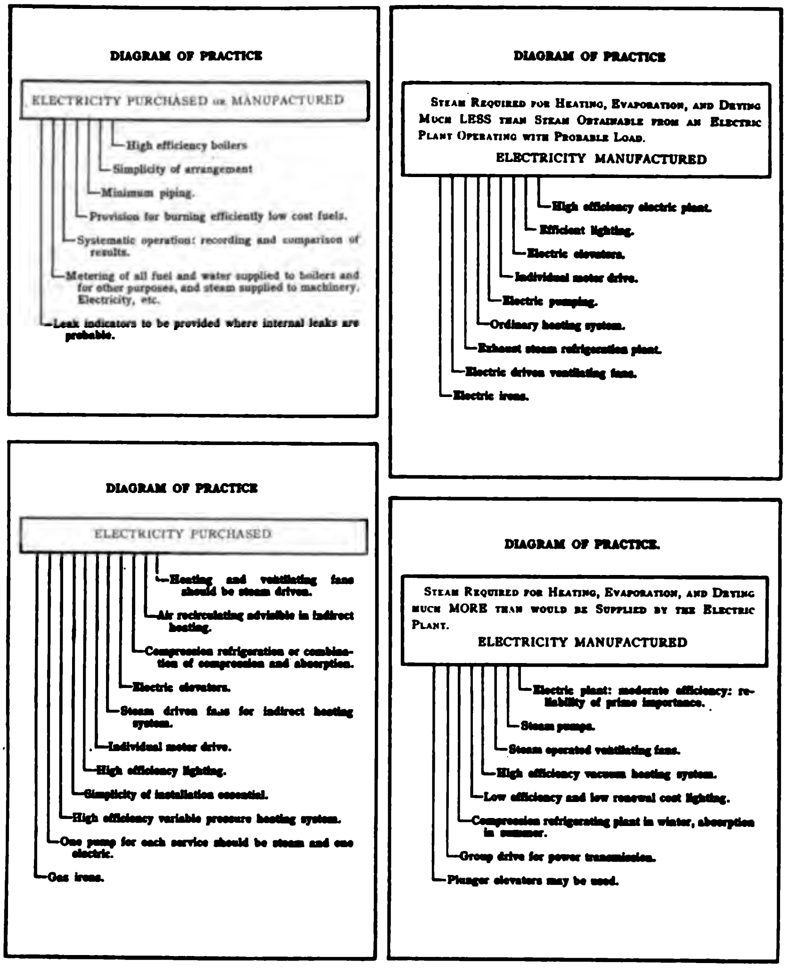


DIAGRAM OF PRACTICE

ELECTRICITY PURCHASED OR MANUFACTURED

- High efficiency boilers
- Simplicity of arrangement
- Minimum piping.
- Provision for burning efficiently low cost fuels.
- Systematic operation: recording and comparison of results.
- Metering of all fuel and water supplied to boilers and for other purposes, and steam supplied to machinery. Electricity, etc.
- Leak indicators to be provided where internal leaks are probable.

DIAGRAM OF PRACTICE

STEAM REQUIRED FOR HEATING, EVAPORATION, AND DRYING MUCH LESS THAN STEAM OBTAINABLE FROM AN ELECTRIC PLANT OPERATING WITH PROBABLE LOAD.

ELECTRICITY MANUFACTURED

- High efficiency electric plant.
- Efficient lighting.
- Electric elevators.
- Individual motor drive.
- Electric pumping.
- Ordinary heating system.
- Exhaust steam refrigeration plant.
- Electric driven ventilating fans.
- Electric irons.

DIAGRAM OF PRACTICE

ELECTRICITY PURCHASED

- Heating and ventilating fans should be steam driven.
- Air recirculating advisible in indirect heating.
- Compression refrigeration or combination of compression and absorption.
- Electric elevators.
- Steam driven fans for indirect heating system.
- Individual motor drive.
- High efficiency lighting.
- Simplicity of installation essential.
- High efficiency variable pressure heating system.
- One pump for each service should be steam and one electric.
- Gas irons.

DIAGRAM OF PRACTICE.

STEAM REQUIRED FOR HEATING, EVAPORATION, AND DRYING MUCH MORE THAN WOULD BE SUPPLIED BY THE ELECTRIC PLANT.

ELECTRICITY MANUFACTURED

- Electric plant: moderate efficiency: reliability of prime importance.
- Steam pumps.
- Steam operated ventilating fans.
- High efficiency vacuum heating system.
- Low efficiency and low renewal cost lighting.
- Compression refrigerating plant in winter, absorption in summer.
- Group drive for power transmission.
- Plunger elevators may be used.

DIAGRAMS SHOWING THE EFFECT OF DIFFERENT BASIC CONDITIONS ON ISOLATED PLANT DESIGN

The electric supply affects the power plant design, the heating system design, the electric lighting design, the refrigeration plant, pumping apparatus, manufacturing equipment.

The refrigerating plant affects the design of the water supply, design of the power plant, both as to size and type of apparatus, pumping plant and ventilating equipment.

The type and design of elevator machinery affects the structural design, and the design of engines, dynamos and storage battery. Although these are not strictly germane to the discussion of the isolated plant, it may be noted that the sprinkler equipment and the plumbing lay-out are also affected by all the items above mentioned.

The diagrammatic representations shown herewith indicate the effects of different basic conditions on plant design.

A fair example of the interdependence and interaction of the modern plant is a new building on Fifth Avenue. It is distinctly a typical office and loft building and contains offices on the upper floors, lofts for show, and sales rooms on the middle stories; and the first four floors are occupied by the owners as a retail store for ladies' wear. The building (173 by 90 ft., 52.7 by 27.4 m.) is 11 stories high and contains basement and a partial sub-basement for the plant.

The various factors that enter in the design of this isolated plant are the following:

(1) Heat must be supplied to keep the building warm and also to warm the air supplied for ventilation.

(2) Basement, first floor and sub-basement have to be very completely ventilated, and as no radiators are permitted on the first floor, the ventilation and heating for this floor are combined. It is particularly important that the air supplied shall be clean and free from dust.

(3) The building must be equipped with sprinklers, and a complete system of fire protection provided.

(4) Water must be pumped and supplied to all toilet rooms, offices, to a number of other locations, as well as to fire standpipes and sprinkler equipment.

(5) Passengers must be carried to and from the various offices and lofts, and a special service of a different class must be furnished for the store's customers.

(6) A fur storage room, 50 by 60 ft. (15 by 18 m.) and 13 ft. (4 m.) high, must be kept at from 20 to 26 deg. fahr. by the circulation of dry refrigerated air. Filtered and refrigerated drinking water is to be provided at a number of points on each floor.

(7) Electricity must be supplied for lighting large spaces and for localized illumination. Electricity must also be furnished to a number of fan and sewing-machine motors, pressing irons and cutters, as well as to the large motors operating the pumps and elevators.

(8) Compressed air must be supplied for elevator door operation, and the air must be exhausted for operating cash system carriers and for vacuum cleaning.

(9) The space below general sewer level must be drained and the drainage discharged into the sewers.

The above nine important functions are to be performed in this modern building. How do they affect each other?

A calculation of the losses through walls, windows and exhausted air shows that the heating of the building does not require as much steam as the required electric plant will give. This indicates, if any electric plant is installed, the necessity of using efficient engines for driving the dynamos; also the use of high-efficiency tungsten lighting when not otherwise objectionable, and the use of electric pumps because of their greater efficiency.

The excess of exhaust steam available also points to the use of a vacuum heating system to keep the back pressure on the electric plant to a minimum.

The effect of the heating design on the ventilating equipment is self-evident, but it is perhaps well to note that the excess of exhaust available points to electric drive for the ventilating fans.

The source of electric supply largely determines the character of the heating system. If the supply of electricity is to be obtained from a central station, a back pressure on the steam heating system would not be objectionable, in fact a steam heating pressure variable at will is advisable; electric pumps and electric-driven ventilating fans are not advisable during the heating season, but high-efficiency lighting becomes even more necessary than before. The refrigerating plant should be steam-driven and probably of the compression type in order to give exhaust steam, while if electricity is made on the premises, the exhaust steam available points to an exhaust-steam-operated absorption refrigerating plant.

Motors will be planned largely for group drive with a plant and for individual drive with purchased electricity.

The refrigeration design has a most important effect on the design of the water supply, as on the size and type of the refrigerating plant will depend the arrangement of water piping, the amount of storage capacity, the method of automatic pump governing and quite possibly the system of water supply risers throughout the building and the decision as to whether it will prove advisable or not to install a well.

The refrigerating design will affect the power plant piping design because of the use in the retort or generator of steam at a higher back-pressure than that carried on the main parts of the plant.

The design of the ventilating equipment will be affected even if cooling of the rooms is not directly planned, because the water used on the refrigerating plant will probably be partly used for air cleansing and cooling in the ventilating plant.

This interdependence of parts could be followed out through all the list, but sufficient has been given to show its extent.

EFFECT OF INTERDEPENDENCE ON GENERAL DESIGN

The close reaction of one factor on another points to two main features frequently neglected in design:

1. Compactness.
2. Simplicity.

If possible, I would place all of the machinery, except the boilers, in one room.

The cross connections between the component parts of the plant make it very advisable that they should be close together, both because of the initial cost and because of the decreased cost of upkeep due to less lengths of pipe, fewer joints, reduced condensation, etc.

As the whole equipment is interacting, it should be under the direct observation of the engineer, and all parts should be clearly in view and not placed off in separate little spaces where leaks and bad performance will not be noticed. Separate pump rooms have been advocated, because pumps always leak.

The unavoidable complexity of the modern heating, lighting, refrigerating, vacuum pumping and elevator equipment makes the utmost simplicity in design necessary.

I do not mean to neglect safeguards, but the excessive duplication of piping and valving to prevent some possible mishap often results in the trouble it is designed to prevent, as the valves and the mains begin to leak through cross expansion strains and neither line can be shut off. Complication of engine valves, cylinders and receivers with a view to decreased steam consumption often wastes more in labor cost than is saved in steam consumption. The possibilities of steam turbine applications to isolated plants, notwithstanding a lower steam efficiency, lie wholly in their simplicity of operation.

Compactness and simplicity are of the greatest importance, and one might add reliability. I do not minimize the importance of steam or electrical efficiency.

In this discussion I am treating more of the design of the whole plant than of any one part. To obtain over-all efficiency of operation the problem must be considered as a whole. An efficient and high-grade heating equipment with equally efficient and high-grade electrical refrigerating and elevator plants may be put together and form a most inefficient isolated plant; and *vice versa*, a poorly planned extravagant electrical system may not affect the over-all efficiency perceptibly if the heating and refrigerating plants absorb all the waste energy.

As an example of the first proposition, I will cite an office building in New York in which every part was of the very highest standard — high-efficiency elevators, steam appliances in a restaurant of the best type, a corliss valve steam-driven refrigerating and ice-making plant, a most complete and efficient electrically driven ventilating system, a most modern water-tube high-pressure boiler and a nearly perfect system of electric installation, but the cost of heat, light, ventilation, power and elevator operation was over double the cost in a similar building, with apparatus much less costly and refined.

The reasons were clear: a high-pressure steam plant with night and day force was required for the refrigerating plant and kitchen steam, so that the operation of an electric plant would have added little to the labor cost, but electricity was purchased, and as this purchased electricity was used to drive the fans of the ventilation system, two things resulted. The electric bill was increased and the steam for heating the air required for ventilation had to be obtained from the boilers. If the fans had been steam-driven and the exhaust from the steam engines been used to heat the air, the electric bill would have been reduced by several thousand dollars and the cost of steam would have been no greater during the heating season when the fans are mainly used.

The water from the refrigerating plant was originally wasted, because the plumber had nothing to do with the refrigerating plant and laid out a perfect system of plumbing, regardless of the other parts.

The elevators were electric and were operated by purchased electricity, and live steam direct from the boilers was used for heating, whereas it might just as well have operated engine and dynamos first and then made power for the elevators.

This installation has since been changed by the addition of a private electric generating plant.. The use of electric-driven ventilating fans and pumps is now entirely correct, because the electric plant gives sufficient exhaust steam for all the heating. The water from the refrigerating plant is saved as far as possible, and it is the intention to install an air washer, through which the excess condenser water will be recirculated, cooling the air and the water at the same time by evaporation. It is of interest to note, in passing, that a gross saving of over $1,000 a month has been obtained since the plant installation. This includes the profit from the sale of steam and electricity to an adjoining building. Regarding the converse proposition that a combination of inefficient apparatus may result in efficiency, it is evident that if the demand for low-temperature steam (250 deg. or less) exceeds the supply available from the private generating plant, even if the electric system is a 240-volt two-wire lighting plant or some similar electricity waster, this loss of efficiency will not affect the over-all economy of the plant materially. Such conditions exist in sugar mills, dye houses, salt blocks, chocolate factories, harness-blacking factories and the greater number of those chemical factories that depend upon evaporation for their product. In city buildings, other than factories, this condition also frequently exists during a part of the year, but seldom during the whole period.

Fuel Used for Heating and Other Purposes

I would like to give figures of pounds of steam used to heat buildings of different types and sizes, but my facts come in dollars and tons; and it is hoped that the discussion will bring out other data.

I have not attempted to derive any formula from these figures. The facts and conditions are given, and while each case will differ from those given, the figures presented should allow an intelligent engineer or owner to estimate closely the probable cost of supplying steam to a building of one of the types given. I use the figures myself and find my estimates prove closely correct.

COST OF FUEL AND LABOR FOR HEATING IN TYPICAL BUILDINGS WITHOUT PRIVATE ELECTRIC PLANTS

Apartment Houses

No. 1.—100 by 100 ft. (30 by 30 m.) 7 stories and basement—21 apartments—one elevator.	
Steam for heating and hot water and pump. Fuel used, No. 1 buckwheat at $3.25 per ton........................	Fuel $1150 to $1250
	Labor $1200 to $1320

No. 2.—200 by 100 ft. (61 by 30 m.) irregular—8 stories and basement—72 apartments—two elevators. Steam for heating and hot water, laundry dryers and pumping. Fuel used costs $2.05 per ton	Fuel	$2350
	Labor	$2276
No. 3.—200 by 92 ft. (61 by 28 m.)—11 stories and basement—block front—77 apartments—elevators. Steam for heating and hot water. Coal for heating. Coal for hot water amounted to 300 tons in a year. Stoves for dryers. Fuel used, pea coal	Fuel	$4317
	Labor	$2800
No. 4.—(Corner)—100 by 100 ft. (30 by 30 m.)—12 stories. Steam for heating, hot water dryers, refrigerating plant and pump. Used 1050 tons No. 1 buckwheat	Fuel	$3700
	Labor	$2465

I have no figures from hotels without private electric plants larger than 50 by 100 ft. (15 by 30 m.), 12 stories. Almost all such hotels in New York have their own plants. Those that have not do not give out their figures.

HOTELS

No. 5.—Apartment hotel. 50 by 100 ft. (15 by 30 m.) 10 stories	Fuel	$2700
	Labor	$1920
No. 6.—High class apartment hotel. 50 by 100 ft. (15 by 30 m.) and annex 25 by 100 ft. (7.6 by 30 m.).—4 stories. Heating, hot water and refrigeration. Absorption system. Low pressure steam	Fuel	$2503
	Labor	$1920

OFFICE BUILDINGS

No. 7.—100 by 100 ft. (30 by 30 m.)—12 stories—corner building. Corner heating and some hot water	Fuel	$1700
	Labor	$2500
No. 8.—Corner—offices—11 stories—86 by 150 ft. (26 by 30 m.). Heating, steam for kitchen and refrigerating plant. Steam for hot water (25 h.p. and up)	Fuel	$3564.65
	Labor	$3746.25
No. 9.—50 and 30 by 197 ft. (15 and 9 by 60 m.). 12 stories—protected on west	Fuel	$1047.50
	Labor	$2020.00
		$3067.50
No. 10.—Offices. Steam for heating. Plunger elevators. Pumping and hot water	Fuel	$4383.35
	Labor	$5798.52
		$10,181.87
No. 11.—Offices 45 by 85 ft. (13.7 by 25.9 m.)—16 stories—corner—three electric elevators.	Fuel	$1,180
	Labor	$ 810
		$1,990
No. 12.—Loft building—50 by 100 ft. (15 by 30 m.)—12 stories, middle of block, protected.	Fuel	$800
	Labor	$420
No. 13.—100 by 100 ft. (30 by 30 m.)—Salesrooms—12 stories. (Corner).	Fuel	$1,580.00
	Labor	$5,798.00
No. 14.—128 by 90 ft. (39 by 27 m.) and 173 by 90 ft. (52.7 by 27 m.)—Mail order house—11 stories and basement. Steam for heating hot water. 4 plunger elevator pumps and house pumps	Fuel	$4,621
	Labor	$4,100

No. 15.—75 by 185 ft. (22.8 by 56.3 m.)—12 stories and basement—middle of block but exposed above lower floors..Fuel $1,280
Labor $713

No. 15 (a).—16 stories—123 by 143 ft. (37.4 by 43.5 m.) (Corner).....Fuel $2700
Labor $ 960

DEPARTMENT STORES

No. 16.—207 by 100 ft. (63 by 30 m.) and 25 by 104 ft. (7.6 by 31.7 m.) and 90 by 75 ft. (27 by 22.8 m.).
Steam for heating, refrigerating and pumps and hot water. Hydraulic elevators. 7000 kw-hr..Fuel $6,583
Labor $6,084

No. 17.—92 by 122 ft. (28 by 39 m.) and 253 by 184 ft. (77 by 56 m.)—7 and 10 stories. yard (anthracite) screenings and soft coal..........................Fuel $5,967
Labor, $5,000

No. 18.—23,000 sq. ft. (2,137 sq. m.)—seven stories—six passenger and three freight elevators (plunger type) No. 1 buckwheat anthracite...............Fuel $4,000
Labor $5,000

No. 19.—200 by 200 ft. (61 by 61 m.)—6 story and basement.
Use No. 2 buckwheat coal..Fuel $5,231
Labor $4,056

No. 20.—Factory and loft building—two buildings about 12,000 sq. ft. (1,579 sq. m.) per floor—6 stories and basement......................................Fuel $1,100
Labor $936

Labor Costs. The figures given opposite labor for each building are within 10 per cent of the actual pay roll.

Some owners engage cheap engineers and firemen and take a chance—others, more careful of their own property and their tenants' lives, have good engineers.

Several disastrous fires could not possibly have gotten the headway they did, nor could such loss of life have occurred, if an intelligent and highly organized power plant engineering force had been on the premises.

Electric Loads. The electric load curves, showing the variation in use of electricity in a number of differing buildings, offer a fair basis for estimating probable requirements under similar conditions.

There is a general tendency to overestimate the maximum electric demand, due in great measure to the possibility of all the lights being in use at one time or of all the elevators starting at once.

Practically speaking, such conditions are not possible, and experience enables us to determine in advance within 10 per cent or 15 per cent what the maximum load will be for a stated size and type of building.

It is for this purpose that the load curves are particularly useful. Such load curves also aid in determining the probable kilowatt-hour use per month or per year, but I find the most convenient method is to compare buildings of similar size and character. For this reason I give data on the quantities used in buildings of various types and sizes.

KILOWATT-HOUR CONSUMPTION OF ELECTRICITY IN BUILDINGS

Lofts and Manufacturing Buildings

No. 21.—185 by 200 ft. (56 by 61 m.)—12 stories, basement and sub-basement, 464,084 kw-hr. All kinds of light manufacturing; 12 elevators; electric heating for manufacturing.

No. 22.—100 by 100 ft. (30 by 30 m.)—12 stories and basement, 180,910 kw-hr. Corner. Four elevators. Printers on top three floors. Holiday goods manufactured on four floors.

No. 23.—100 by 100 ft. (30 by 30 m.)—12 stories and basement, ventilating plant, 212,483 kw-hr. Four elevators. Cloak and suit manufacturing. Middle of block.

No. 24.—100 by 100 ft. (30 by 30 m.). 12 stories. Corner. Textile salesrooms; 180,000 kw-hr.

No. 25.—75 by 185 ft. (22.8 by 56.3 m.). 12 stories and basement; 140,000 kw-hr. Four elevators. Silk salesrooms and cloak manufacturing.

No. 26.—44 by 100 ft. (13.4 by 30 m.). 12 stories and basement; 100,000 kw-hr. Two elevators. Cloak and suit and other manufacturing.

No. 26 (a)—123 by 143 ft. (37.4 by 43.5 m.) 16 stories—corner. No manufacturing. 240,000 kw-hr.

Office Buildings

No. 27.—50 by 140 ft. (15 by 42.6 m.). 12 stories and basement; 143,320 kw-hr. Four electric worm-gear elevators.

No. 28.—85 by 150 ft. (26 by 45.7 m.). 11 stories and two basements. Restaurant on first floor. Stores and sales lofts on three floors. Five elevators. 260,000 kw-hr.

No. 29.—100 by 100 ft. (30 by 30 m.) 12 stories; 1 basement corner; 4 elevators; no restaurant. Radiator and vacuum cleaner store on first floor. 187,000 kw-hr.

No. 30.—55 by 100 ft. (16.7 by 30 m.) 12 stories and newspaper offices; five high-speed electric elevators. 600,000 kw-hr.

Hotels

No. 31.—100 by 100 ft. (30 by 30 m.) 12 stories and 2 basements; three electric worm-gear elevators; one sidewalk lift; laundry machinery; transient trade. 325,000 kw-hr. (from ammeter record).

No. 32.—50 by 200 ft. (15 by 60 m.) 12 stories and basement; no laundry; four electric worm-gear elevators. (ammeter record.) 240,000 kw-hr.

No. 33.—50 by 100 ft. (15 by 30 m.) 12 stories and basement; small laundry; two electric elevators; absorption ice machine; 100,000 kw-hr. (watt-hour meters).

Apartment Houses

No. 34.—Five houses covering block 500 by 100 ft. (152 by 30 m.); 6 stories and basement; tenants pay for electricity; five electric elevators; small stores under one building; moderate priced apartments. 125,000 kw-hr.

No. 35.—200 by 100 ft. (60 by 30 m.) irregular; 8 stories and basement; two elevators; steam pumps; 72 medium priced apartments. 85,000 kw-hr.

No. 36.—200 by 92 ft. (60 by 28 m.) 11 stories and basement; four elevators; electric pumps; 77 apartments; tenants pay for electricity. 100,000 kw-hr. (approx.)

No. 37.—100 by 100 ft. (30 by 30 m.) 12 stories; corner; 3 elevators; tenants' light included in rent (48 apartments), 114,000 kw-hr.

No. 38.—200 by 100 ft. (60 by 30 m.) 12 stories and two basements, with annex 50 by 100 ft. (15 by 30 m.) 8 stories and garage; tenants pay for electricity; electric pumps half year; lavish public lighting. 193,000 kw-hr.

Department Stores

No. 39.—230 by 100 ft. (70 by 30 m.) (irregular); 7 stories and two basements; plunger elevators; arc lighting for selling part; tungsten for other portions; steam-driven cash blower fans and pumps and elevators. 600,000 kw-hr.

No. 40.—92 by 122 ft. (28 by 37 m.) and 184 by 253 ft; 7 stories and 10 stories; tungsten lighting; electric elevators; absorption ice machine and steam pump. (Lighting inadequate) 900,000 kw-hr.

No. 41.—200 by 300 ft. (60 by 91 m.) 8 stories; one and one-half basements; plunger elevators; lighting excellent; service of highest grade cash blowers; electrically driven conveyers; electrically driven ventilating plant. Approximate kw-hr. 2,300,000.

LOAD CURVES

The curves presented herewith are taken from hourly readings, noted on regular log sheets, of which sample forms are reproduced from an office building, an apartment house and an industrial plant.

The readings are, in all cases, the nearest to the steady load readable; that is, the engineer waits until the cessation of the jump caused by an elevator or several elevators starting before noting the current. Probably the readings usually include some of the running current, because, while there are many periods even in a busy building when the elevators are not drawing current, these intervals are infrequent and hard to catch.

Discussion of Load Curves. Load curves 1 and 2 show the variation in electric load in two apartment hotels. No. 1 is a hotel catering mainly to high-class permanent residents, built on a plot 50 by 200 ft. (15 by 61 m.)—12 stories and basement—containing four electric elevators, 10-ton refrigerating and ice-making plant, the usual kitchen steam-using appliances, but no laundry. The hotel has 300 guest rooms and 200 baths, hence the demand for hot water is an important factor. All the water used is pumped to a tank above the roof.

There are about 1000 outlets for lights and the total connected capacity is about 100 kw., excluding elevator motors.

The elevator load, which is extremely variable, is equalized by a storage battery. The hotel has had its own plant for over seven years, abandoning central station supply. The maximum load occurs from six to eight o'clock p.m. and is about 100 kw. This includes about 20 kw. charging current. The ratio of maximum load to connected capacity is therefore 80 per cent.

This ratio is very high because the number of outlets installed is restricted to the minimum requirement consistent with sufficient light.

Curve 2 shows the conditions in another hotel, a large, imposing structure covering a block front in New York City, which is 17 stories above ground and two below, built on a plot approximately 210 by 205 ft. (64 by 62.4 m.). This building contains housekeeping apartments, as well as the ordinary hotel rooms, restaurant kitchen and laundry.

Refrigeration is supplied to the housekeeping apartments, as well as to the kitchen and restaurant, and cooled drinking water is also circulated throughout the building.

The elevators (about 17) are all of the hydraulic plunger type, DAILY LOG SHEET OF INDUSTRIAL PLANT Wednesday, January 11, 1911.

	Gen. No. 1		Gen. No. 2		Gen. No. 3		Gen. No. 4		Gen. No. 5		Exciter No. 2		Rotary No. 2				Steam plant				
																	Temperature		Steam pressure		
Time	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	A.C. Amps	Amps Field	D.C. Volts	D.C. Amps	F. W.	Cond. W.	High	Rec	Vac.
6 a.m.	6200	15		15		16	125	1600		1600	110	58	6.6	7.3	125	440			142	33	
7 "	6200	16		16		17	125	1750		1750	110	58	6.6	7.3	125	460			144	35	
8 "	6000	17		17		17	125	1500		1500	110	58	6.1	7.3	125	420			145	36	
9 "	6000	17		17		17	125	1600		1600	110	58	6.5	7.1	125	440			145	36	
10 "	6000	16		17		17	125	1600		1600	110	58	6.5	7.2	125	440			145	36	
11 "	6000	17		17		17	125	1500		1500	110	58	6.2	7.3	125	420			144	35	
12 m.	6200	16		17		17	125	1500		1500	110	58	6.2	7.3	125	440			142	33	
1 p.m.	6000	16		17		17	125	1700		1700	110	58	6.5	7.3	125	440			140	30	
2 "	6000	19		19		19	125	1700		1700	110	58	6.5	7.3	125	460			140	30	
3 "	6000	18		18		18	125	1600		1600	110	58	6.3	7.2	125	440			142	33	
4 "	6000	18		18		19	125	1650		1650	110	58	6.0	7.2	125	420			143	34	
5 "	6000	18		18		19	125	1500		1500	110	58	6.4	7.4	125	430			143	34	
6 "	6300	13		13		14	125	1650		1650	110	60	6.4	7.8	125	440			145	36	
7 "	6400	13		13		13	125	1700		1700	110	60	6.6	7.8	125	460			145	36	
8 "	6400	12		12		13	125	1700		1700	110	60	6.6	7.8	125	440			144	35	
9 "	6300	14		14		14	125	1800		1800	110	60	6.6	8.0	125	460			142	33	
10 "	6400	12		13		13	125	1900		1900	110	60	6.8	8.0	125	460			140	30	
11 "	6400	12		12		13	125	2050		2050	110	60	6.6	8.0	125	440			140	30	
12 "	6300	14		14		15	125	2000		2000	110	60	6.4	7.8	125	430			143	34	
1 a.m.	6400	12		13		13	125	1950		1950	110	60	7.0	8.0	125	480			143	34	
2 "	6300	12		13		13	125	1900		1900	110	60	7.0	8.0	125	480			145	36	
3 "	6300	12		13		13	125	1950		1950	110	60	7.0	8.0	125	480			145	36	
4 "	6300	12		13		13	125	1900		1900	110	60	7.0	8.0	125	480			145	36	
5 "	6300	12		13		13	125	2000		2000	110	60	6.6	7.8	125	440			145	36	

Chief Electrical Engineer

DAILY LOG SHEET OF INDUSTRIAL PLANT Wednesday, January 11, 1911.

	Gen. No. 1		Gen. No. 2		Gen. No. 3		Gen. No. 4		Gen. No. 5		Exciter No. 2		Rotary No. 2				Steam plant				
																	Temperature		Steam pressure		
Time	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	A.C. Amps	Amps Field	D.C. Volts	D.C. Amps	F. W.	Cond. W.	High	Rec	Vac.
6 a.m.	6200	15		15		16	125	1600		1600	110	58	6.6	7.3	125	440			142	33	
7 "	6200	16		16		17	125	1750		1750	110	58	6.6	7.3	125	460			144	35	
8 "	6000	17		17		17	125	1500		1500	110	58	6.1	7.3	125	420			145	36	
9 "	6000	17		17		17	125	1600		1600	110	58	6.5	7.1	125	440			145	36	
10 "	6000	16		17		17	125	1600		1600	110	58	6.5	7.2	125	440			145	36	
11 "	6000	17		17		17	125	1500		1500	110	58	6.2	7.3	125	420			144	35	
12 m.	6200	16		17		17	125	1500		1500	110	58	6.2	7.3	125	440			142	33	
1 p.m.	6000	16		17		17	125	1700		1700	110	58	6.5	7.3	125	440			140	30	
2 "	6000	19		19		19	125	1700		1700	110	58	6.5	7.3	125	460			140	30	
3 "	6000	18		18		18	125	1600		1600	110	58	6.3	7.2	125	440			142	33	
4 "	6000	18		18		19	125	1650		1650	110	58	6.0	7.2	125	420			143	34	
5 "	6000	18		18		19	125	1500		1500	110	58	6.4	7.4	125	430			143	34	
6 "	6300	13		13		14	125	1650		1650	110	60	6.4	7.8	125	440			145	36	
7 "	6400	13		13		13	125	1700		1700	110	60	6.6	7.8	125	460			145	36	
8 "	6400	12		12		13	125	1700		1700	110	60	6.6	7.8	125	440			144	35	
9 "	6300	14		14		14	125	1800		1800	110	60	6.6	8.0	125	460			142	33	
10 "	6400	12		13		13	125	1900		1900	110	60	6.8	8.0	125	460			140	30	
11 "	6400	12		12		13	125	2050		2050	110	60	6.6	8.0	125	440			140	30	
12 "	6300	14		14		15	125	2000		2000	110	60	6.4	7.8	125	430			143	34	
1 a.m.	6400	12		13		13	125	1950		1950	110	60	7.0	8.0	125	480			143	34	
2 "	6300	12		13		13	125	1900		1900	110	60	7.0	8.0	125	480			145	36	
3 "	6300	12		13		13	125	1950		1950	110	60	7.0	8.0	125	480			145	36	
4 "	6300	12		13		13	125	1900		1900	110	60	7.0	8.0	125	480			145	36	
5 "	6300	12		13		13	125	2000		2000	110	60	6.6	7.8	125	440			145	36	

Chief Electrical Engineer

Time	Amperes									Volts
	Lighting circuits									Circuits
	1	2	3A	3B	4A	4B	5	Unb. load	Bells	Lights
7 a.m.				240	240	240				115
8 "				300	300	300				115
9 "				325	325	325				115
10 "				340	340	340				115
11 "				340	340	340				115
12 n.				340	340	340				115
1 p.m				330	350	350				115
2 "				350	350	350				115
3 "				350	350	350				115
4 "				350	350	350				115
5 "								1000		115
6 "								1600		115
7 "								1750		115
8 "								1750		115
9 "								1650		115
10 "								1300		115
11 "								1200		115
12 m.							700			115
1 a.m.							460			115
2 "				340						115
3 "				300						115
4 "				300						115
5 "				340						115
6 "				200	200	200				115
Total				4765	3485	3485	1160	10250		115

RUNNING TIME.

Name of machine		A.M.												P.M.										
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	1
Boiler	No. 1																							
"	" 2																							
"	" 3																							
"	" 4																							
"	" 5																							
"	" 6																							
Engine	" 1																							
"	" 2																							
"	" 3																							
"	" 4																							
"	" 5																							
"	" 6																							
Injector	" 1																							
"	" 2																							
Feed pump	" 1																							
" "	" 2																							
Ele. "	" 1																							
" "	" 2																							
" "	" 3																							
" "	" 4																							
Pneu. "	" 1																							
" "	" 2																							
Brine "	" 1																							
" "	" 2																							
" "	" 3																							
Ice water "	" 1																							
" "	" 2																							
Ammonia "	" 1																							
" "	" 2																							

DAILY LOG SHEET OF OFFICE BUILDING

Date April 3, 1911.

Time	Amperes							Volts		Steam		Temperatures					Pressures		
	Generators					Battery				Boiler press.	Back press.	F. W.	H. W.	Brine		Room	Ammonia		Brine
	1	2	3	Total	Neut.	Charge	Disch.	Plant	Batt.					In	Out		Head	Back	
7 a.m.	110	110		220		50		240	220	110	4			5	6	92	115	5	25
8 "	125	125		250		50		240	280	110	5			6	5	94	115	5	25
9 "	200	200		400		50		240	260	110	5			6	5	94	115	5	25
10 "	230	230		460		50		240	260	110	5			8	7	94	115	5	25
11 "	245	245		490		50		240	260	110	5			9	8	96	115	5	25
12 "	155	155	155	465		50		240	260	110	5			9	8	96	105	5	25
1 p.m.	155	155	155	465		50		240	260	110	5			9	8	96	105	5	25
2 "	165	165	165	495		50		240	260	100	5			11	10	98	105	5	25
3 "	165	165	165	495		50		240	260	110	5			12	11	98	105	5	25
4 "	175	175	175	525		50		240	260	110	5			15	14	100	105	5	25
5 "	170	170	170	510		50		240	260	110	5			15	14	100	105	5	25
6 "	155	155	155	465		50		240	260	110	5			13	12	100	105	5	25
7 "		125	125	250		50		240	290	110	4			12	11	100	105	5	25
8 "			125	125				210		105	3			11	10	100	105	5	25
9 "			100	100				240		105	3			11	10	100	105	5	25
10 "			75	75				240		105	3			12	11	100	115	5	25
11 "			60	60				240		100	3			14	13	98	115	5	25
12 "			50	50				240		100	3			14	13	98	115	5	25
1 a.m.							30		250	100	3			12	11	98	115	5	25
2 "							25		240	105	3			10	14	98	115	5	25
3 "							25		240	100	3			9	8	98	115	5	25
4 "							35		240	100	3			7	6	96	115	5	25
5 "		45		45				240		105	3			7	6	96	115	5	25
6 "		75		75		50		240	270	105	3			5	4	96	115	5	25

	Water meters			
	A. M. and Co.		Maillard	
	No. 1	No. 2	Croton	Tank
Pres. read.....	4,244,930	91,670	509,490	316,240
Prev. read.....	4,240,750	91,450	506,390	315,780
Difference......	4,180	220	3,100	460

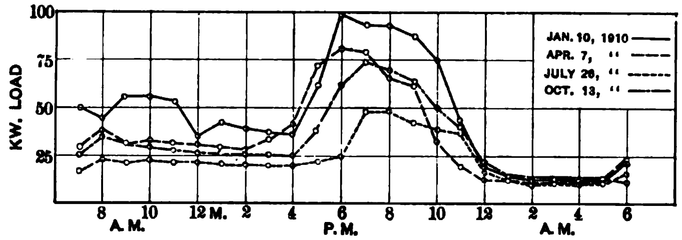
	Watt meters		
	No. 1	No. 2	No. 3
Pres. read.	2890	2129	9026
Prev. read.........	2,846	2,015	8,942
Difference..........	54	114	84
Constant...........			
Kw. hours.........			
Total kw-hr........			
Boilers in use......	X	X	

Average temperature—Fair.
Condition of bearings—A.M.
Condition of bearings—P.M.

SUMMARY.—Fuel, 18,900 lb.; Ashes, 24 cans; Eng. Oil, 2 qts.; Cyl. oil, 4 qts.; Lamps, 33.

Chief Engineer.

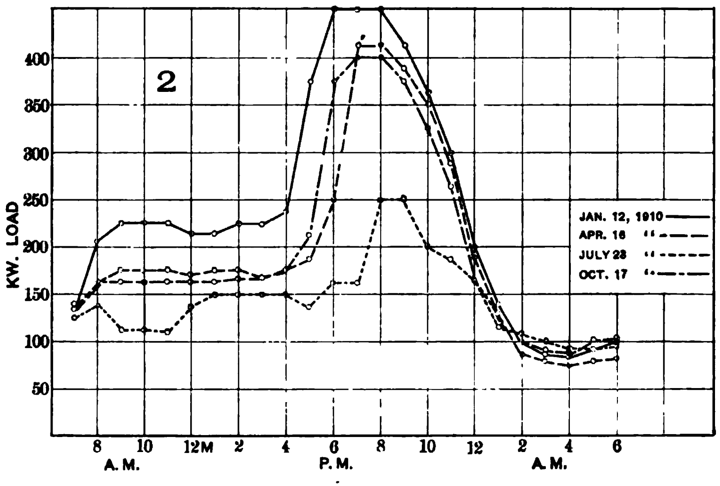
operated by compound and triple pumps. The ground floor contains a number of handsome stores, brilliantly illuminated, while the rest of this floor is given up to public rooms and restaurant.



Curve 1—Hotel

The approximate connected capacity of lighting is 750 kw. and the maximum load is 450 kw. from 6 to 8 p.m.

The ratio of maximum load to connected capacity is therefore about 60 per cent.



Curve 2—Apartment Hotel

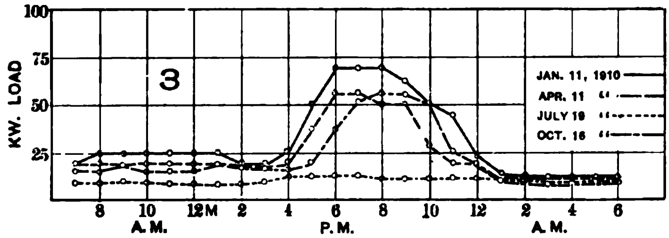
In this hotel the electric plant seldom uses over 300 h.p. during the day and 600 h.p. at night, whereas the boiler horse power developed frequently exceeds 1000.

The balance is made up of the steam supplied to elevator pumps, half a dozen other steam pumps, laundry, kitchen and refrigerating plant.

During the cold weather the exhaust steam from all the apparatus does not suffice to heat the building, and additional boiler steam is needed.

It is not unusual in the building to burn 40 tons of fuel in a day, and 50 tons have been burned in extreme weather. This latter consumption indicates an average of 1000 h.p. for the whole 24 hours. During the cold season it is evident that the electricity is really a by-product of the heating, in so far as the fuel is concerned. A distributive test showed that the electric plant used about seven-eighteenths of the total steam supplied.

Curves 3, 4 and 5 show conditions in high-grade housekeeping apartment houses. The three curves represent different conditions.

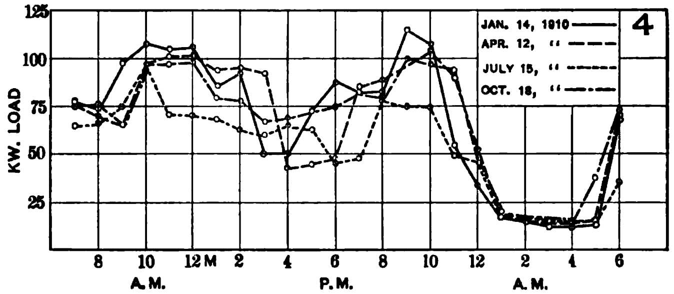


CURVE 3—APARTMENT HOUSE

Curve 3 is an apartment house in which electricity is supplied free with rent. The refrigerating plant and pumps are steam-driven. The building is twelve stories and basement, and the apartments are large, 34 in all which rent from $3,000 to $4,000 per year. The building has its own electric and refrigerating plant, electric elevators, but no storage battery.

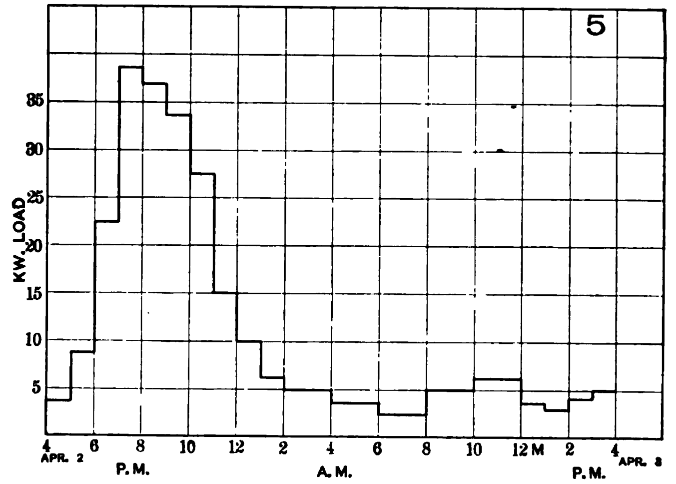
The curve shows the steady load, and elevator fluctuations are additional and reach as high as 30 kw. The connected capacity, excluding elevators, is 100 kw. The ratio of maximum load to connected capacity is 70 per cent.

Curve 4 is from an apartment house of the highest class, in which electricity is sold to the tenants at the standard central station rates, although made on the premises. The building covers a block 200 by 100 ft. (61 by 30 m.), 12 stories and basement, containing 48 apartments. The different character of this load curve is largely due to the operating of an electrically driven 15-ton refrigerating machine. A large storage battery acts as auxiliary to the electric plant, and at one o'clock every morning the engines are stopped and the electricity is supplied from the battery.



Curve 4—Apartment House

Curve 5 is an apartment house, two elevators, with 72 apartments, which rent for about $280 to $300 per room per year. The building covers a block and has 8 stories and basement. The maximum load is 38 kw., exclusive of elevators, and the connected capacity about 100 kw. The ratio of maximum load to connected capacity is about 40 per cent.



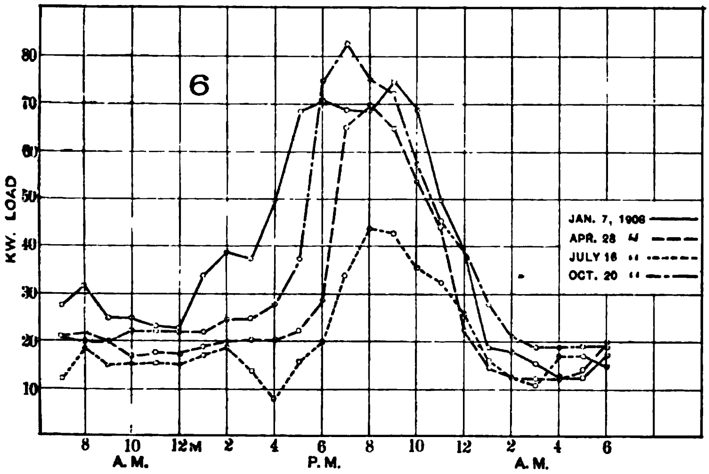
Curve 5—Apartments

Curve 6 shows the electric load variations in an apartment house of the best grade. The apartments are of from five to fourteen rooms, renting at from $1,000 to $5,000 per year. They have artificial cold storage, complete porter service and a vacuum steam heating system among the "modern improvements." There are seven electric elevators for eighty-seven apartments.

Electricity is made on the premises, but it is sold to the tenants at the regular central station rates after being metered.

The connected capacity exclusive of elevators is over 200 kw. and the maximum load is 75 kw. (The 82-kw. load on October 20, 1908, was due to special decorative lighting.)

As this 75 kw. includes about 12 kw. battery charging current, the ratio of maximum load to connected load is actually about 30 per cent. The effect of metering is clearly indicated if the ratio of maximum load to connected load in Curve 3, 70 per cent, is compared with this ratio of 30 per cent.

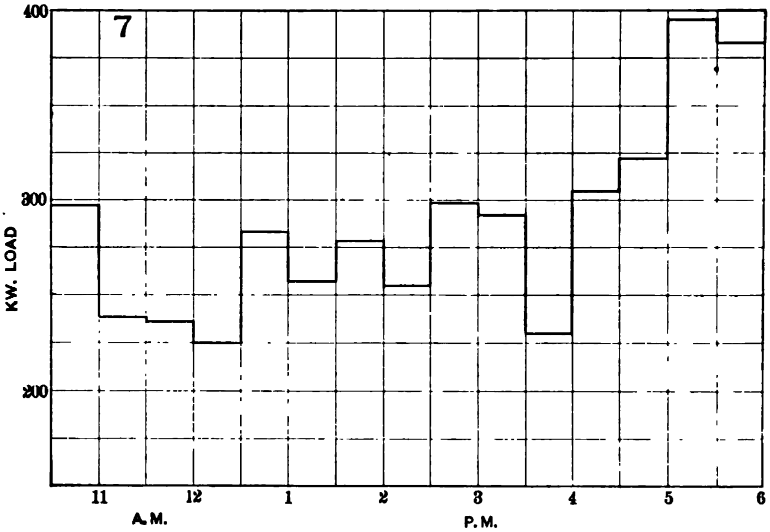


Curve 6—Apartment House

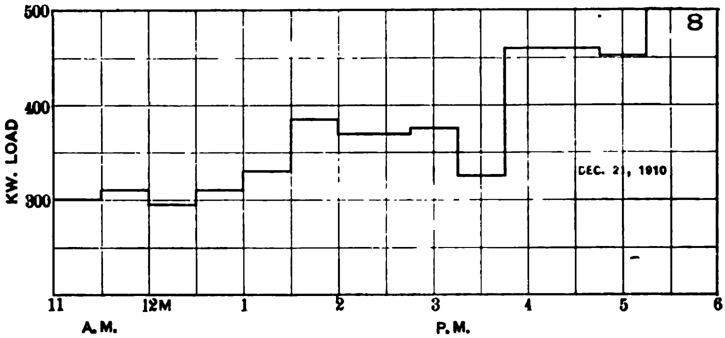
Curves 7 and 8 are maximum load curves in two department stores in New York, catering to customers in moderate circumstances. The connected capacity was not obtainable, but from installations in other department stores a ratio of 60 per cent may be safely assumed as the ratio of maximum lighting load to connected lighting capacity.

In so far as the power is concerned, the character of the service is all-important. If the motors are connected to elevators, the maximum sudden, momentary demand with four or more elevators will not exceed one-half the sum of the rated starting currents, and where there is a large number of elevators, this ratio will drop to one-third.

Curve 9 is a load curve of a large dry goods store, taken on January 26 and May 16. The maximum load in December reached 10,000 amperes at 110 volts or 1100 kw. The connected capacity, excluding spare apparatus such as a second motor for driving a reserve exhauster for cash system, was over 2000 kw., or omitting the motors, approximately 1600 kw.

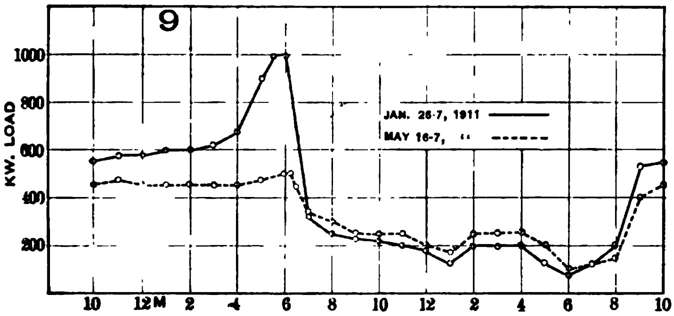


CURVE 7—DEPARTMENT STORE



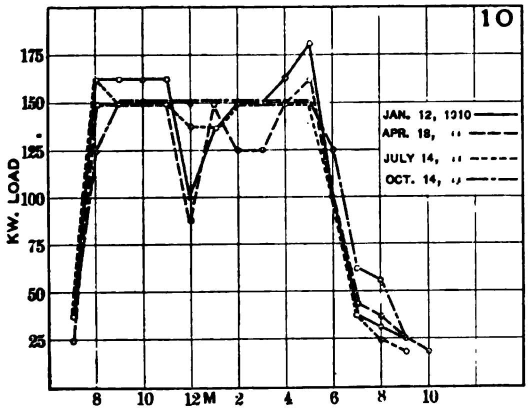
CURVE 8—DEPARTMENT STORE

The ratio of maximum lighting load to connected lighting load is in this store somewhat less than 60 per cent. Curves 11 and 12 are typical of loft buildings devoted to light manufacturing, such as shirtwaists, cloaks, suits, lingerie, etc. Curve 10 is from one of the oldest and best known of the modern 12-story buildings. It is 185 by 200 ft. (56 by 61 m.) and enclosed on two sides, having twelve elevators, besides four sidewalk lifts.



Curve 9—Department Store

The curves show the steady load, the fluctuation due to elevator load being additional.

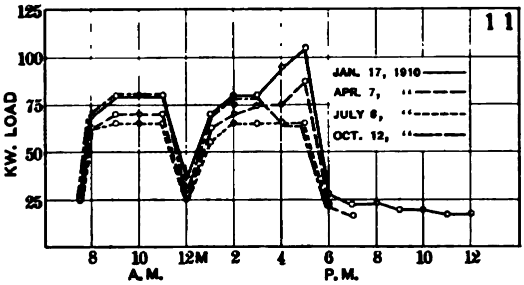


Curve 10—Loft Building

Curve 11 is from a similar building on a corner 100 by 100 ft. (30 by 30 m.) 12 stories, with four elevators.

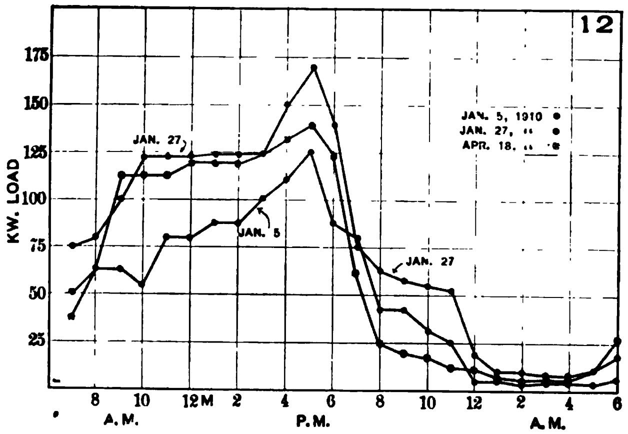
Four floors and the basement are occupied by the owners of the building, and are used for the manufacture and display of holiday goods, picture postals, etc. The other floors are leased, three to a printing firm. This firm's use accounts for the night load.

The connected capacity in these buildings is 251 kw. motors plus 336 kw. elevator motors and 214 kw. plus 100 kw. elevator motors respectively, and the ratio of maximum load and connected capacity is 36 per cent for building No. 11 and 35 per cent for building No. 12.



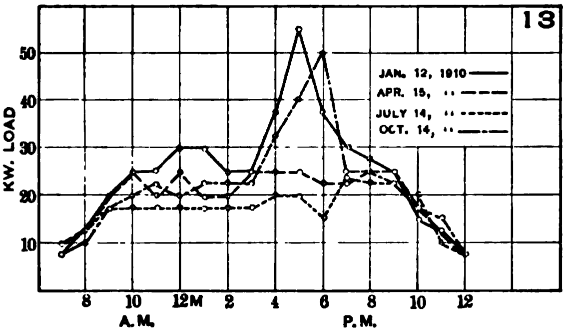
Curve 11—Manufacturing Loft Building

Curves 12 and 13 are from typical office buildings. Curve 12, taken January 27 and April 18, includes the electricity supplied to a 12-story building 50 by 100 ft. (15 by 30 m.), abutting into the south. (January 5 curve covers the original building only.)



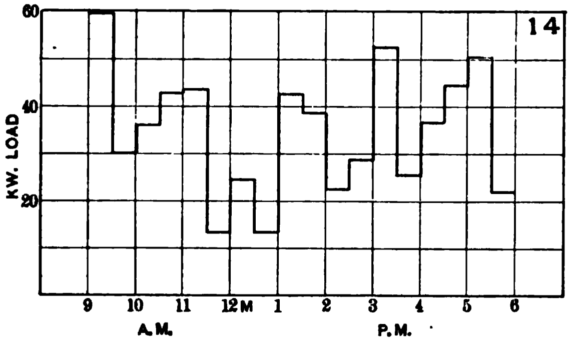
Curve 12—Office Building

This building contains five elevators and the abutting building contains three. These are supplied through a storage battery and the load curves include about 25 kw. of charging current. The ground floor basement is occupied mainly by a restaurant and a store. A very complete electric-driven ventilating equipment is installed for both of these.



CURVE 13—OFFICE BUILDING

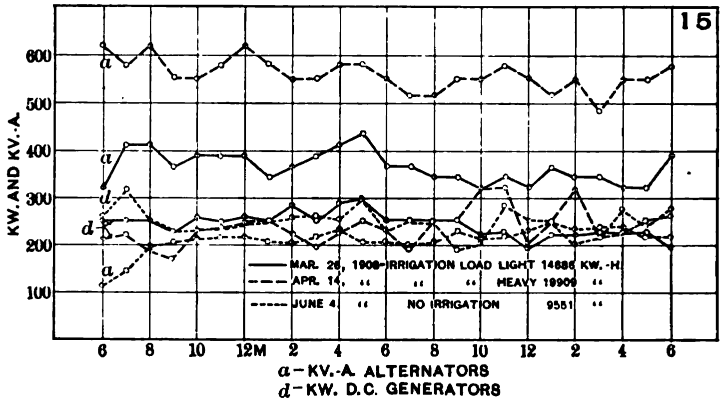
Curve 13 is from another office building on a corner 100 by 100 ft. (30 by 30 m.) and has four elevators but no storage battery. This load curve shows steady load as nearly as possible. The connected capacities are 375 kw. and 212 kw. respectively, and the ratios of maximum load to connected load are 44 per cent and 26 per cent.



CURVE 14—MERCANTILE BUILDING

Curve 14 is a typical load curve of a mail order house. The elevators are hydraulic plunger type, so the curve shows the electricity used for lighting and for the operation of sewing machines, phonograph motors and other small motors.

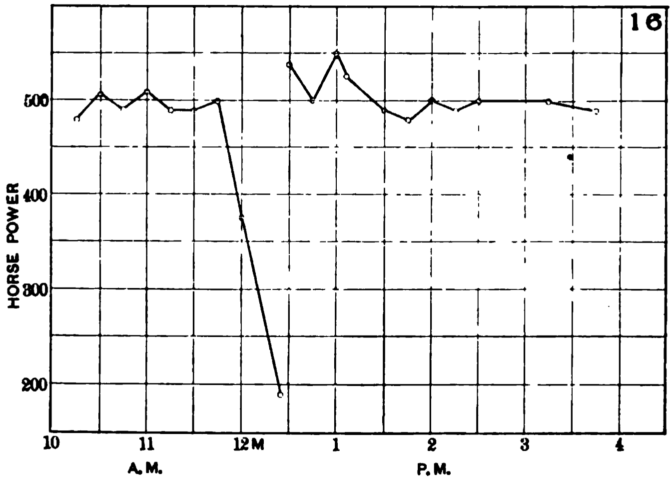
The connected capacity of this installation is approximately 188 kw., and the ratio of maximum load to capacity is 32 per cent.



Curve 15—Sugar Mill

Curves 15, 16 and 17 are industrial load curves.

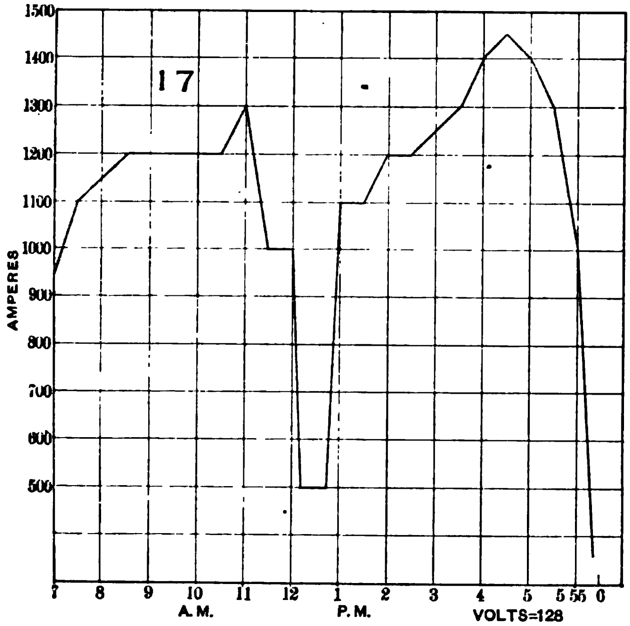
No. 15 is from an immense sugar mill. No. 16 is from a jute mill and No. 17 from a malleable iron foundry. (The last represents only the load of a producer gas engine unit and cannot be taken as the whole shop load. It is given here merely for illustration.)



Curve 16—Jute Mill

Load Curve Characteristics. The electric load curves of the hotels show a daily running load from 8 a.m. to 3 p.m. of from one-quarter to one-third the maximum load, and a peak load from dusk to midnight or 11 p.m. of from one-half to full maximum load, depending upon the season.

The apartment houses where electricity is paid for, show a day load, deducting charging current, of from one-seventh to one-eighth the maximum load, with the usual peak from dusk to 11 p.m. of about ¾ maximum load, except in summer when it falls to one-half. When light is included in the rent, the day load varies from one-seventh to one-third the maximum, and the peak load except in the summer is about three-quarters of the maximum.



Curve 17—Iron Foundry

The department store shows a steady day load, from 9 a.m. until 4 p.m. in the winter, and until closing time in the other seasons, of about two-fifths the maximum load, and the night lighting for cleaning, etc., varies from one-fifth to one-tenth the maximum.

The office building without restaurant has a day load of from one-third to two-fifths the maximum load, and there is no peak except during the winter and fall months.

The office building with restaurant and ventilating fans has a day load of about two-thirds the maximum, and the peak load lasts about two hours.

The manufacturing loft building has a steady load except during the noon hour of three-quarters to seven-eighths of the maximum. The lesser load during the summer months in one case is due to the stopping of the printing plant. The peaks seldom last longer than one hour.

The industrial plants have similar curves, *i.e.*, steady load with comparatively small peaks for about an hour.

With these load curves and others, as a basis for design, the division of the isolated plant into suitable units is not difficult, if the probable tendency of the building can be gaged in advance. In the following discussion, a unit is intended to mean an engine dynamo, with its switchboard, piping and accessories.

For a hotel or apartment house a three-unit plant, each unit having a capacity of half the maximum demand, will leave one unit always in reserve; one will operate the equipment during the light load periods, and the two during peak load, with good over-all efficiency and perfect reliability. If electric elevators are installed, a storage battery to equalize the fluctuations while the dynamos are operating and to carry the small lighting load from 1 a.m. until 6 p.m. while the dynamos are shut down is a valuable and advisable adjunct, not only as an economizer of fuel, but also to insure freedom from voltage variation.

In large plants like that of the hotel illustrated in Curve 2, it may be advisable to make the plant a four-unit plant, two of the units having each one-sixth the capacity required for the maximum demand. One of these operated after midnight will then supply all the service.

In the loft and manufacturing buildings, two large units, each capable of carrying the full load, and one small unit for after-hour service, are advisable, unless the fixed charges on the extra initial cost of the two large units over a three-unit plant with each unit equal to one-half the maximum demand, more than equals the saving obtainable by the operation of one unit instead of two.

As the cost of the two-unit plant is usually at least one-quarter more than the three-unit plant, this question requires careful consideration, but simplification and space conditions point *a priori* to the two-unit equipment.

The same conditions hold with department store equipments, but another factor of grave importance enters, *viz.*, continuity of operation.

Darkness in a department store during a busy season might cause a panic and would almost certainly mean loss, hence it is advisable to have two units actually operating during all the selling time, or at least during peak load period, so that if anything should occur to prevent one machine from supplying light, the other would be immediately available. Hence it is customary and advisable to have at least three large units and one small one for late night service.

Office buildings of the ordinary type come under the same grouping as the hotels and apartments. The peak is of much shorter duration, and one of the units may be of less efficient type than the two regularly operated engines, if the size of the plant makes such a distinction advisable.

A storage battery is particularly advisable in most office buildings that are equipped with electric elevators, because the elevator load is a very large and sudden addition to the regular running load, and even with the perfected modern mechanical and electrical governors, some fluctuation in the lights is liable to occur. Of more importance in this connection is the small but necessary night lighting and the power required for a night watchman's elevator service, for both of which the storage battery is admirably adapted.

For factories occupied by a single owner, a single-unit plant is adopted in most instances, because of its simplicity and the usual reliability of the slow-speed engines and dynamos ordinarily adopted for such installations. Such an equipment has its serious drawbacks, particularly in starting a new plant, where some unforeseen and hidden trouble in manufacture may cause untold annoyance, if it develops after the regular running is commenced.

If ample time can be had to test out the apparatus beforehand, little trouble need be feared with a single unit where the schedule of 10 or 11 hours a day is adhered to.

POWER PRODUCTION IN ISOLATED PLANTS

I have already pointed out the influence of the different factors upon each other in the isolated plant. The choice of a prime mover is necessarily governed by these factors.

If heating is a negligible matter, as it is in tropical countries and in many manufacturing and industrial establishments, the choice of a prime mover is governed by the balance between investment and efficiency.

The high-efficiency modern producer gas engine and the oil engine by their simplicity and reliability offer many advantages over the high-pressure steam plant, and where steam is not used for other purposes to an extent proportioned to the power requirements, the tendency is rightly, I think, toward this type of plant.

Two producer gas engine plants recently installed have given results fully equal to the guarantees, and a kilowatt-hour can be and is regularly produced at the switchboard under regular operating conditions for about two pounds of No. 1 buckwheat anthracite or pea coal, and this in plants of a few hundred kilowatts capacity.

One of these plants, of 175 kw. capacity, of which the load curve is given, is making current for 1.14 cents per kilowatt-hour, including fixed charge on a power house, etc., for a duplicate equipment. These are the owners' figures and include all charges.

The other plant, a 600-kw. plant divided into three units, is using 1.75 pounds of pea coal per kw-hr. under regular working conditions, including all fuel used for banking.

As the cost of the gas producer plant is no higher than that of a high-efficiency steam plant, the relative merits under the conditions outlined hardly need elaboration.

On the other hand, in another plant, belonging to the same company for which the gas engine plant was installed, the steam engine offered the correct solution for at least part of the plant, because the electricity was practically a by-product of the concentration and evaporation of the sugar solutions.

In many instances a combined steam engine and producer gas or oil engine plant offers the best solution, the steam plant being installed to such extent only that its exhaust may be fully utilized.

With such equipments, with the exhaust gases from the gas engine used to heat feed water from the boilers, an almost ideal operating condition exists for at least part of the year.

I have investigated a number of isolated plants operated by oil engines, and find particularly in the small plants that they are giving remarkable service. The almost universal testimony is to the absence of trouble and the reliability of the small sets. With the larger units the heavy parts and the unfamiliarity of the operators have given some trouble, but in general the results are satisfactory.

The necessity for steam boilers and the space conditions in city buildings usually preclude any type of plant but steam unless the building is planned from its inception for the gas engine or oil engine equipment. As the engineer is frequently not called in until the general plan is adopted and as space beyond a certain amount is often extremely precious, the usual isolated plant in city buildings in the East is a steam plant.

COSTS OF MAKING ELECTRICITY

Some kilowatt-hour costs in buildings follow. These costs are derived by deducting from the total operating cost of the building with an electric plant, the cost of operating without an electric plant. This latter cost is either actual or estimated, depending upon whether street service had been used prior to the installation of the private plant or not. In each instance the fact is stated. I do not go into particulars of each plant because there have been many such figures printed. They are, however, as closely correct as I can make them and are taken from the regularly monthly plant reports.

Where the costs are given for different seasons, the variation is due of course to the high cost of supplying heat and engineer's services, etc., during the winter and the relatively low cost of these services during the summer.

The kilowatt-hour costs do not include fixed charges unless otherwise stated.

My reason for excluding fixed charges is that each case presents a different condition. Money may be worth 25 per cent to one man and 3 per cent to another. With the cost of making electricity before him, each man can then decide if this cost is sufficiently less than the central station charge to warrant the investment.

KILOWATT-HOUR COSTS

Loft building.—100 by 100 ft. (30 by 30 m.) 12 stories and basement.

Month	Kw-hr.	Total cost	Basic cost	Mfg. cost	Mfg. cost per kw-hr.
April	15080	756.81	300	456.81	$0.03
January	18450	936.26	470	466.26	$0.0252
October	17810	884.76	300	484.76	$0.0328
July	12060	680.26	200	480.26	$0.04

Cost of plant: $12,000. Fixed charges per kw-hr. approximately ¼c.

Loft building.—185 by 200 ft. (56 by 61 m.) 12 stories and two basements.

Month	Kw-hr.	Total cost	Basic cost	Mfg. cost	Mfg. cost per kw-hr.
April	36930	1830.25	750	1080.25	$0.029
January	41950	1841.82	950	891.82	$0.0212
October	39480	1643.07	750	893.07	$0.0226
July	31800	1543.04	650	893.04	$0.0281

Fixed charges: ½ cent per kw-hr. Plant cost, $20,000.

Apartment house: (free light); 36 apartments, high class refrigeration; best service.

Month	Kw-hr.	Total cost	Basic cost	Mfg. cost	Mfg. cost per kw-hr.
April	17450	1359.86	1016.85	343.01	$0.0197
January	21620	1360.84	1052.29	308.55	$0.0142
October	13500	1208.67	900.75	307.92	$0.0228
July	9350	1074.03	709.82	364.21	$0.0389

Apartment house: (Electricity sold to tenants) 87 apartments; high class refrigeration; best service; large quantity public lighting.

Month	Kw-hr.	Total cost	Basic cost	Mfg. cost	Mfg. cost per kw-hr.
April					
January	18154	2224.59	1749.18	475.29	$0.0261
October	14885	1920.56	1507.34	413.22	$0.0278
July	11254	1731.54	1226.66	504.88	$0.045

These items are all higher than usual because last year the plant was completely overhauled, new plates installed in storage battery, new condenser for refrigerating plant, new hot water tank, etc., all of which is charged off during ten months from date of expenditure.

Office building: 100 by 100 ft. (30 by 30 m.) 12 stories; tungsten lighting; four elevators.

Month	Kw-hr.	Total cost	Basic cost	Mfg. cost	Mfg. cost per kw-hr.
April	14600	738.15	365.62	372.53	$0.026
January	18310	714.39	458.40	255.99	$0.0142
October	15060	669.69	355.03	314.66	$0.021
July	11590	693.17	250.00	443.17	$0.04

Office building: 140 by 70 ft. (42.6 by 21 m.) 10 stories.

Total kw-hr. 340,000 of which 88,817 were used mainly for driving an electric pump for operating two high-speed plunger elevators. 255,788 kw-hr. for lighting.

Total cost per year	$8,070
Basic cost (estimated)	$3,200
Cost of electricity	$4,870
Manufacturing cost per kw-hr	1.43 cents

MANUFACTURING PLANTS

Locomotive Works—oil engines.

Total cost per kw-hr. on 225 h.p. set (including 0.223 cent for fixed charges)........0.74 cent.

5300 hours a year at full load.

Shop time 6500 hours.

With load factor another year, after panic, of only 24%, cost per kw-hr. was increased to........2 cents.

Malleable Iron Foundry: Producer Gas Plant.

Total cost per kilowatt-hour including fixed charges, approximately..1.71 cents.

Hardware: (Steam plant condensing). These figures include interest and depreciation and are given through courtesy of Mr. T. Hoops, Jr., Supt. of Wilcox Crittenden & Co., Middletown, Connecticut.

1908

Month	Kilowatts	Cost
May	23,970	0.01986
June	27,760	0.01733
July	29,600	0.01602
August	27,530	0.01736
September	27,830	0.01601
October	26,180	0.02095
November	22,360	0.02289
December	24,960	0.02164

Silk Mill: Producer Gas Plant. (New York City); 150 by 100 ft. (45.7 by 30 m.) 4 to 5 stories high.

In week's run of 56 hours	4208 kw-hr.
2.6 pounds of pea coal per kw-hr. approximate cost including fixed charges	2½ cents.

Department Store: 250,000 kilowatt-hours.

Cost per kilowatt-hour	1.34 cents.

Hotel: (based on figures given by chief engineer).

Cost of operation with plant	$33,285.71
Cost of operation without plant	
Cost exclusive of electricity purchased	25,779.71
Cost of making electricity	$ 7,407.00
Cost per kw-hr	between 6/10 and 7/10 cents.

Hotel: 300 rooms; 12 stories; 240,000 kw-hr.

Total operating cost	$12,800
Basic cost (based on operation before plant was installed)	$ 8,600
	$4,200
Cost per kw-hr	1.75 cents.

TABLE OF COST PER KILOWATT CAPACITY

(Based on personal experience in New York and vicinity)

	Per kw. of plant capacity
Boilers (erected and set in masonry):	
Horizontal-tubular	$14—$18
Water-tube	16— 20
Steam engines:	
High-speed, simple direct-connected	20— 25
Medium-speed, compound non-condensing direct-connected	28— 35
Low-speed, compound condensing, belted	20— 25
Low-speed, simple, belted	25— 30
Gas engines	50— 60
Oil engines	75— 85
Gas producers	15— 20
Dynamos:	
Direct-connected to high-speed engine	13— 16
Belt-connected to engine	12— 15
Direct-connected to corliss engine	16— 20
Switchboard	5— 10
Foundations	5— 10
Steamfitting—including auxiliary apparatus—such as feed heater, grease separator, exhaust head, tanks, covering, etc	20— 30

The figures of installation cost have been published by me before and I use them in estimating and find them to be closely correct for New York City.

I hope that these figures together with the other data presented will be of use and will also serve as a basis for discussion and presentation of other facts and figures.

DISCUSSION ON "SOME NOTES ON ISOLATED PLANTS" (MOSES), NEW YORK, JANUARY 12, 1912.

R. P. Bolton: I will draw attention to some of the features which the author has introduced as being of an informative nature and upon which we are invited to base future action and practise, and of which the diagrams presented purport to be indexes or guides. A casual observation shows that they omit consideration of a very important element of variation in output and demand on the part of these appliances. They seem to be based upon the sole consideration as to whether electricity be purchased or be manufactured, in the case of those on the left side of the page, and on the further consideration, in the case of the right-hand diagrams, of whether a certain amount of steam, more or less, would be required and provided by the apparent electrical output. The isolated plant, however, operates under summer conditions and under winter conditions, the demand for steam heat being climatic, intermittent, and irregular, while the demand for electric lighting is also intermittent and irregular—therefore how can conditions as laid down in the diagrams be used to determine the relative proportions or even the kind of apparatus to be installed in different plants? It is an open question whether or not it is desirable for steam-driven fans to be installed for indirect heating systems in connection with purchased electricity. The conditions might be such that it would be highly undesirable from an economic standpoint to make such a combination, and more particularly so if the process involved the employment of extra labor, which after all is the main element to be considered in connection with all the items in these diagrams, and one which does not appear in them at all.

It is a remarkable and interesting fact, which appears very frequently in connection with isolated plant design and operation, that low efficiency and wasteful lighting is regarded as an element which does not disturb the overall efficiency of the isolated plant.

I cannot agree that the building on Fifth Avenue, mentioned in the paper, is typical of office building conditions, for the diagram (Curve 12) shows that the load curves of its plant are not typical of office building duties. One curve illustrated shows the apparent output used in the building, and another that of the building combined with the output used in another building, an interesting combination, to be sure, but one which does not carry with it conviction. Nor does the information given in connection with the building allow an analysis which would offer necessary directions to a designer in planning a new plant upon similar bases.

In regard to office building curves, there is a great deal omitted from the paper which would have been of value. These buildings are operated, in this as well as in other cities, on low factors of load and also on low factors of time, operating the plant on a ten or twelve-hour service, on the working days of the year, which, including the Saturday half-day service, are equivalent to 278 days of 10 or 12 hr. The rest of the year is made up of lost or idle time on Saturdays, Sundays, and public holidays, and the night periods of all, resulting in a combination of conditions very unfavorable to the operation of steam and other generating apparatus. In the Trinity building, No. 111 Broadway, the maximum peak load in October, which may be taken as an average of the year's condition, occurs at 4:30 o'clock, and has a tendency to shift as the winter proceeds, occurring at an earlier hour in the afternoon, and then gradually shifting to a later hour. The building is equipped with the highest class of machinery to be secured at the time of its installation, and has units of a sufficient number to divide the load in a reasonable manner, and with a reasonable expectation of efficiency, yet on an October day, when the load reached about 3000 amperes, at 4:30 p.m., the all-day load factors were as follows: of the sets under steam, 37.6 per cent; of the total installation, 28.22 per cent.

Inasmuch as all classes of small steam engines fall off very rapidly in efficiency, and increase their steam consumption very rapidly, as the load factor decreases, the conditions must be very unfavorable to economical operation. When conditions occur such as on holidays, summer afternoons and during night service, poor economy results. A typical Sunday load on December 3 was as follows: the all-day load factor 12.21 per cent of the sets under steam, and only 3 per cent of the entire installation. Such conditions are not, therefore, favorable to the operation of steam engines.

I draw your attention to the fact that some of the diagrams of load curves presented omit a very essential element, the variations introduced by elevator service, which constitute a certain proportion of swinging load above the load here recorded. For the purpose of comparing and deciding upon the proportions of another plant, under similar circumstances, what information can be gained from diagrams consisting of observations of a steady load, irrespective of the surges of elevator service, inasmuch as elevator service constitutes an element of prime importance in all plants of any magnitude to-day?

The author introduces daily log sheets of records in certain classes of buildings. It is evident upon a glance at these sheets, that many of the elements which were supposed to be recorded are omitted, and that they do not afford any definite information, either by summarization or by note, such as may enable anyone to derive any determinate conclusions therefrom.

John C. Parker: I am very glad to see that Mr. Moses has laid stress upon the fact that the isolated plant should be treated as a whole. I think we too often in our engineering practise are likely to concentrate attention on details, insisting on perfection here, perfection there, or perfection in the other place, without considering whether the aggregate of perfections constitutes perfection in the whole. The fact that the isolated plant is to be handled as an entity rather than as a group of disjunct units, is one on which stress can very advantageously be laid. This is so much the case that it becomes very important that the isolated plant be considered not only as an electrical energy generating device, but as a heating device as well. This fact makes it rather regrettable that Mr. Moses has given a good many of the details of cost of fuel and labor for heating in buildings without private electric plants, in a general form rather than specifically. The fuel consumption of a building of a certain size, of certain superficial area, with a certain number of floors and used for certain business, is not in itself particularly valuable. The conditions in different manufacturing plants vary so much that even had the fuel consumption for heating purposes been given, that would not in itself have been sufficient evidence, because climatic conditions in various localities differ, the percentage of glass in the exposed walls of buildings naturally differs with the style of architecture, and the character of the construction of the side walls makes a tremendous amount of real difference in the fuel consumption for heating.

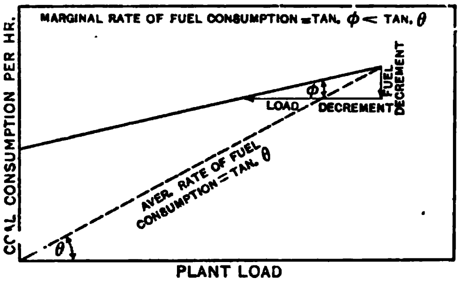
It is quite unfortunate that Mr. Moses has not reduced the extensive data in his paper to formulas, so that the members could have the benefit of his experience in deriving the constants of various buildings for heating purposes. I think it would be a considerable contribution to our records if, in his final summing up of the discussion, Mr. Moses could reduce some of the data secured in his extensive practise to formulas. Those of us who have to calculate the heating requirements of buildings find a tremendous dearth of data giving the building constants.

In regard to the table of costs of plants per kilowatt capacity, I notice that for a medium speed direct-connected plant we might expect the investment cost to run between $90 and $125 per kilowatt. My own experience in investigating something like 500 industrial plant propositions has indicated that these figures are perhaps a little low for plants of the best type and of medium size—say up to 500 kw. The discrepancy between my own observation and that of Mr. Moses may be due, perhaps, to the fact that these plants have not required a building, and I have failed to find the stack cost represented in the tables in Mr. Moses' paper. Where a plant is put in a basement or sub-basement, no separate building has to be put up for it, but one would still expect to find some part of the building cost chargeable to the plant.

I ask if Mr. Moses intended the figures to cover the overhead costs, which I suppose might add anywhere from $4 to $10 a kilowatt to the cost of the plant.

I am very much interested in one point brought out in Mr. Moses' paper, and that is that the highest efficiency apparatus is not always to be sought—that there are times when, as Mr.

Bolton expressed it, the less economical the apparatus, the more economical it really is in operation. I think the principle can be pushed a little further than Mr. Moses has done in his paper. It is not altogether a matter of running a plant to supply exhaust steam, but we do find differentiating conditions, between purchased power and isolated plant power, if you will, due to still another cause. We find that the use of highly efficient power-utilizing apparatus and lamps may be desirable in one isolated plant and not in another. The reason is this: unless the isolated plant has approached the limit of its capacity, the installation of highly efficient lighting units, we will say, will make reduction in only two places; namely, the fuel and the water cost. I will roughly indicate this by a diagram, which is not intended to be quantitative. The aggregate fuel may be plotted as ordinates, and the kilowatts load as abscissas. The curve then might be expected to be something in the nature of a straight line intersecting the ordinate axis at some distance above the origin. Now, in cutting the load off from the top, we find that while the average fuel consumption of the plant might be something like five or six pounds (2.3-2.7 kg.) per kilowatt-hour, the reduction in fuel consumption by drawing off load would not be in anything like the ratio of five or six pounds to the kilowatt-hour, but in a much smaller ratio, since the reduction in fuel consumption is at the point where the consumption is the most economical. Fuel consumed on the light load part of the plant has borne all the burden and heat of the day, and it therefore follows that the eleventh-hour consumption follows the biblical analogue and gets through very easily. Now, from this it follows that, except in the cost of a plant which is pushed to the limit of its capacity, one cannot afford to spend a great deal on highly efficient motor drive, and on efficient lighting units, as could be done where power is purchased from the outside, since in the former case no saving is made in plant investment, labor cost, et cetera, and at the best, an incommensurably small saving of fuel and water; while in the latter case a reduction in load affects equally the kilowatt-hour consumption and the kilowatt demand.



Practically all sales rate schemes are based on three charges:

one a customer charge, which is not affected by anything you may do in the way of efficient operation; another charge based on the kilowatt demand, which is, of course, affected by efficient operation; and another charge based on the kilowatt-hours of energy, a condition which would be similar in a degree to the condition in the laying out of a contemplated isolated plant. There, if your lighting load, or the economies you would make by highly efficient power distributing apparatus, were relatively small, you might be able to get along with a smaller plant.

However, even in this case, the general principle still obtains, since plant cost will follow a curve approximately of the same sort as shown above, and therefore efficient distributing and consuming devices will save only a part of the fuel and water, none of the labor, and only the cheapest part of the apparatus investment.

The point I wish to make in all this is that what the economists know as the " law of diminishing returns," otherwise expressed by the writer in his paper on fixed costs presented before the Institute March 10, 1911, as the " marginal principle," must be applied to all of our studies, without assuming that because efficiency is to be sought at a price in one case, it may of necessity be the desideratum in all cases.

To show just how far the principle brought out by Mr. Moses does apply, I want to take the very simple case of the carbon and the metallic filament lamp. I have assumed the ordinary 16-c.p. carbon lamp, consuming 3.5 watts per candle, and compared it with a 20-watt tungsten lamp, delivering the same amount of light, 16 c.p. There is a difference of 36 watts in the consumption of the two lamps. Assuming a life of 1000 hours for the lamp, and assuming that the marginal coal consumption is 2 lb. (0.9 kg.) (by the marginal coal consumption, I mean the coal consumption due to the last portion of the load added to your plant) and figuring the cost of the fuel, and water evaporated by the fuel, at $3 per ton, we find that the use of the tungsten instead of the carbon lamp will save 10.8 cents during the life of the 20-watt tungsten lamp. Now, on the other hand, let us assume we are purchasing power. Taking figures merely typical, not pertaining to any particular locality, let us assume the power is purchased on a demand charge, we will say of $2 per kilowatt per month, and in addition to this, at 1.5 cents per kilowatt-hour of energy consumption. The saving by the use of the tungsten lamp over the carbon lamp would be 36 watts, times the thousand hours of lamp life, divided by 1000 to reduce to kilowatt-hours, times the 1½ cent charge per kilowatt-hour, or 54 cents, to which is to be added a further reduction of 0.046 kilowatts at $2 for 1000 hours, divided by 200 hours, the assumed monthly hours of burning, which equals 46 cents. This makes a total of $1 saving, as against something less than 11 cents in the case of the isolated plant, where you are not pushing the limit of plant load.

This illustration is a simple one that I thought would be interesting as laying further stress on the fact brought out by Mr. Moses that the higher efficiency apparatus is not always the best; that the isolated plant is not able to avail itself of the efficient devices that can be used with purchased power, where the consumer is not dependent upon a fixed investment.

Please note that the principle here laid down is not of necessity always applicable against the isolated plant, but that in general it does apply when the plant is not being pushed to the limit of its capacity; and that even in the design of a brand new plant, one cannot always take advantage of such a principle, unless the demand load reduction is big enough to make a material difference in the size of plant installation, and then only to a partial degree.

It must not be thought, as might superficially be done, that the greater saving by the use of efficiency apparatus in the case of purchased power is due to the inherently higher cost thereof, but rather that this greater saving can be effected through a flexible rental of the station equipment.

Arthur Williams: I have some reluctance in attempting to present to you the other side of the question that has been so carefully and ably presented to you to-night. At the outset perhaps it is only fair to say that I personally stand on the other side of the question, partly because of my professional relationship to the industry, and partly because I believe that that is the side of economy and efficiency, and of the greatest benefit to those who need modern service in modern buildings.

The author states that the installation of a private plant in one building last year, or the year before, effected an economy of $12,000, or approaching $12,000. The admitted figures are that a gross saving of about $11,500 was effected, of which the consulting engineer received one-third, between $3,000 and $4,000, thus reducing the saving to the owners by that amount, or, let us say, to $7,000. This $7,000 is made up of a number of economies that the consumer himself might have availed himself of. The consumption of current was increased to such an extent that there would be an estimated saving, at the normal rate prevalent in New York, of $3,000 a year. I understand that it cost about $30,000 to put the plant in, and allowing as little as 15 per cent a year to cover interest, depreciation and repairs, you will see the difference is immediately and automatically wiped out.

It is not necessary for me to point out that depreciation need not be the question of the physical life of the plant. It arises from the supersession element, either from improved machinery, or from similar service being obtainable from another source. I do not think the premise can be fairly questioned, that instead of 15 per cent, the depreciation of the first year was 100 per cent, and to whatever actual cost is shown by the books of this consumer should be added the cost of installing the plant, in the neighborhood of $30,000.

The author makes reference to the fire protection to be obtained through the presence in the building of a large engineering force. I regret exceedingly the immediate occurrence of an illustration which shows how utterly incorrect is any such conclusion. I have in mind, and perhaps you all have, the fire which occurred this week, that of the Equitable building, where the engineers, because they were in the building, spent fourteen minutes according to some witnesses, according to others, twenty minutes, trying to extinguish the fire themselves. It is a well known fact that the first three or four minutes are of supreme importance in the extinguishing of a fire. And I submit to you that if that building had had no engineering staff, simply a janitor on duty at night, or a watchman, the first thing such a man would have done would have been to send in an alarm to bring out the fire department. If that had been done—I do not speak with personal knowledge—but if that had been done, our competent fire department would have extinguished the blaze before the lapse of twenty minutes, which expired between the time the fire was discovered and when the alarm was sent in. I am of the opinion that the building most simply equipped, with least dependence on its own equipment, from the standpoint of safety alone, is the best kind of investment, leaving out all other considerations.

In conclusion, I would like to draw your attention to two facts. Mr. Parker, I think, will permit me to say that he need not be surprised that the cost of the stacks is omitted, because it is the usual practise, and I have yet to find a single instance where excavation in solid rock many feet down into the ground, to be replaced with very expensive steel structure, has ever yet entered into the cost of the power plant in the building in the figures of the engineers or architects, nor has it been included in the final cost of the expense of the power plant. When Mr. Parker understands that is a common practise in New York, I do not think that he will be surprised that the cost of the stack has been omitted. In a very recent case we found on an expensive Broadway corner that there was absolutely no difference in the net income upon $800,000 spent in the erection of a 12-story building, taking street service, with all the economies that means, and an 18-story building in which the income from the additional building equipment was required to meet the enhanced expenses of putting a complicated power plant into the building. In the last analysis the percentage of the return on the value of the property was better in the erection of a 12-story building with street supply than an 18-story building with a private plant.

George W. Martin: Mr. Moses' paper presents data showing the cost per kilowatt-hour of generating electric current in a private plant.

During the last few months two cases have come to the writer's knowledge, in which the method of figuring operative costs is open to criticism. In conversation with the superintendent of one of the well known buildings on Broadway, the question of the cost per kilowatt-hour came up. As the plant contained hydraulic machinery for elevator operation, it was necessary to segregate the elevator operating costs in order to obtain the cost per kilowatt-hour of electric generation. This was done by running the electric plant for one Sunday, carrying the same load as on week days. In this way, as the superintendent naively stated, the cost per kilowatt-hour was found to be 2½ cents, not counting repairs. The cost per kilowatt-hour including repairs is left to the imagination.

The item of depreciation is another that is often neglected. Some of the most difficult facts to impress upon the minds of any plant owners, and indeed some engineers, are that the plant is steadily growing older, that repairs are necessary each year, and that depreciation is as real a charge as the coal bill. The neglect of the item of depreciation alone has in one case, to the speaker's knowledge, well nigh resulted in the total shut-down of one of our largest office buildings.

For years this plant was operated apparently with the idea that the machinery would last forever, and as long as a pipe did not actually burst or a boiler explode, little attention seems to have been paid to the fact that the apparatus was steadily growing older. Of course, the small amount spent for repairs cut down the cost per kilowatt-hour. But not so very long ago the plant absolutely refused to work under this system of management, and it was only by the most strenuous efforts that operation was maintained.

The plant is now being entirely overhauled, and in three months the items of repairs for running have been about as follows:

New steam piping	$3,600.00
Repairs to boilers	2,500.00
Repairs to heating system	2,500.00
Miscellaneous repairs	1,000.00
Additional labor necessary to keep plant in operation —two men for six months at $18 each per week	864.00
	$10,464.00

The foregoing items represent actual experience, and demonstrate the absurdity of trying to keep down plant costs by neglecting the items of repairs and depreciation.

Charles K. Nichols: The author of the paper states that "if electricity is made on the premises the exhaust steam available points to an exhaust-steam-operated absorption refrigerating plant;" on the following page he avers that the "refrigerating design will affect the power plant piping design because of the use in the retort or generator of steam at a higher pressure than that carried on the main parts of the plant." In other words, it is the exhaust from the pumps of the absorption refrigerating plant, or other auxiliaries, that is used in the generator of the absorption machine and not the exhaust from the electrical generating units, as one is given to believe from the paragraph first quoted.

While it is unquestionably true that exhaust steam may be used in the generator of an absorption machine, provided a sufficiently high back-pressure is carried to meet the conditions imposed by the temperature of the water that is available for cooling—which is usually high during the summer months when the refrigerating load is at its maximum—it is most assuredly an extremely uneconomical method of attempting to utilize the exhaust from the generating units of the average isolated plant, and if the writer of the paper can point out any single instance where a private electrical generating plant in this city is utilizing the exhaust from the engines of the generating units in the generator of a refrigerating or ice-making plant of the absorption type during any portion of the year, I will be very glad of the opportunity to become acquainted with such an example of the "interdependence and interaction" upon which the author places such stress in connection with isolated power plant design.

The author states, referring to the subject of isolated plant design, that "compactness and simplicity are of the greatest importance" and then, as an evident afterthought, he remarks, "one might add reliability." The sentence last quoted is literally true if applied to the operation of the average isolated plant, and the added reliability is usually obtained in the form of an adequate break-down connection with the central station. The owner of an isolated plant, as well as those persons who are dependent upon one for their supply of light and power, would be inclined to look upon reliability of operation as being of considerably greater importance than either compactness or simplicity of design.

The figures given on the "cost of fuel and labor for heating in typical buildings with private electrical plants," are practically valueless in so far as they afford a means of estimating these items of cost for other buildings. In spite of the author's assurance that "the figures presented should allow an intelligent engineer or owner to estimate closely the probable cost of supplying steam to a building of one of the types given," they actually permit of nothing of the sort, inasmuch as the heating requirements of different buildings of the same general type of construction vary in accordance with the amount of wall and window exposures, and not in accordance with the ground areas covered and the number of stories. It is not at all unusual to find two buildings of practically the same size and the same general character where the heating requirements of one of the buildings are practically double what they are in the other, due entirely to a difference in the exposures. When such buildings are compared on a proper basis, however, these apparent discrepancies entirely disappear.

Even if the heating requirements of these buildings could be sufficiently determined from the data presented to serve as a basis for comparison with other buildings, the actual coal requirements, except for buildings 1 and 2, could not be estimated from the figures of coal cost as given, on account of the omission of the price of coal per ton.

While the figures are represented, from the heading under which they appear, as being fuel and labor costs for heating, they actually cover, in at least fifty per cent of the cases cited, by the author's own admission, the cost of producing steam for other purposes than heating the building. It will be observed that several of the buildings have steam-driven refrigerating plants, while a number of them have hydraulic elevators, operated by steam-driven pumps. It is manifestly useless to present fuel and labor costs, even if they are correct, for installations of this character, if the purpose is to present heating cost figures that may be used for comparative purposes.

The figures presented of kilowatt-hour consumption in various buildings are of little value in so far as they attempt to furnish a means of estimating the probable consumption of electrical energy in a proposed building of known size and type. The author fails to mention, in connection with fourteen out of twenty-two buildings, whether the elevators are of the electric or hydraulic type, a knowledge of which would be quite essential in order to estimate the consumption of electrical energy. In practically none of these cases is any information given as to the character of the lighting or as to the type of electric lamp that is employed. Moreover, the author fails to mention whether a private electrical generating plant is operated in the building or whether electrical energy is purchased from the central station. When a building secures a supply of electrical energy from an isolated plant, the consumption is invariably greater than it is in the case of a similar building which secures its supply of electrical energy from the central station. Where a private generating plant is installed, there is little or no incentive to practise economy in the use of electrical energy, as a result of which a reasonably low unit cost of generation may actually mean a relatively high total cost of furnishing the amount of electrical energy that is actually required.

The method described by the author of obtaining the cost of generating electrical energy in an isolated plant might be a proper one where the conditions permit of an actual determination of the so-called basic cost, but the method becomes a farce when it is necessary to estimate this basic cost.

The author states that these " basic costs " are " either actual or estimated, depending upon whether street service had been used prior to the installation of the plant or not." As the number of cases where central station service has been superseded by an isolated plant is small, it follows that the " basic cost " figures of the author are nearly all " estimated."

John W. Lieb, Jr.: If an examination is made of the schemes of operation of the plant, or diagrams of auxiliary operating practise, which the author has presented, it will be quite apparent that there has been an endeavor by the use of non-electric apparatus in one case and electrically driven auxiliaries in the other, to change what would be the logical selection of auxiliaries so that it would have a tendency in one case to elevate abnormally the production of electrical energy for the sake of getting a larger output over which to distribute unit charges and fixed costs, and to depress them uneconomically in the other case.

S. N. Clarkson (by letter): Mr. Moses has presented a most interesting and instructive paper on a subject which has become an issue in most of our large cities. The statistics quoted would indicate that conditions in New York are quite different from those existing in some other cities—St. Louis, for instance.

Private plants in St. Louis get the benefit of soft 10,000-B.t.u. coal at $1.40 per ton on the cars, but they have to compete with central station rates, which are lower than in New York. Under these conditions the private plant is making but little headway and those which are already in are gradually being replaced by outside service. To make my statement more specific, I will quote the figures which are now available for the year 1911, on plants of 50 h.p. capacity and over. During that period 24 isolated plants aggregating 5285 engine h.p. were converted to central station service and six plants aggregating 585 engine h.p. were put in. Out of the 585 h.p. installed, 265 h.p. went into one laundry.

Directors of commercial enterprises are beginning to realize that they are justified in giving the power companies an apparent bonus over and above their own plant costs because the simplicity, continuity of service and freedom from the effects of miners' and engineers' strikes are worth money to them, and then again there are many items of plant expense, especially in a factory, which cannot be separated from the general expense accounts.

The most representative apartment houses, hotels, office buildings, department stores, metal working factories, electrotypers, chemical works, bakeries, paint manufacturers, stone and marble works, clothing, coffee and spice houses, some branches of wood working, printers and many other industries are buying light, power and in some cases heat from the St. Louis public utility companies. It will be noted that in this list are some lines of business which are considered by many engineers to be the exclusive domain of the isolated plant.

It is true, as stated in the paper, that most stationary engineers believe central stations to be their natural enemy, although if they looked at the matter in a broad light all their fears would vanish. Cheap power promotes manufacturing in any locality and no men are better able to apply themselves in factories than the trained stationary engineers. All negotiations, however, concerning a plant, are naturally conducted with the owners or managers, and as a class they will always be found ready and willing to furnish whatever data are necessary to arrive at a true comparison of the costs of operation. As intimated by Mr. Moses, the public utility companies do not accept unprofitable business, it being generally conceded that the day of the commercial philanthropist is yet to come.

The design of an economical power plant for a factory is difficult for the reason that a single unit is in almost every case insisted upon by the owner and then it must be of sufficient capacity to take care of a large growth in business, which is always hoped for, but sometimes does not materialize until the plant is worn out. In addition to the burden of inefficient operation the plant has to carry high fixed charges in proportion to the actual power demands of the factory. When such a plant is shut down and connection made to the power company's lines, and this is no uncommon occurrence, the fixed charges still go on and are an unnecessary handicap as compared with a competitor's factory in which central station service was installed originally.

There is a growing tendency among consulting engineers to advise their clients to install outside service at the outset, while at the same time making provision for the installation of a private plant at the end of a year or more of operation in the event of central station service not being what was expected. It is fully realized that in actual practise most isolated plants become less efficient and more costly to operate as years go by, while the service of our public utilities is gradually becoming cheaper. The reasons for the increased costs of private plant operation, as time goes on, are not far to seek. First, the plant is given but secondary consideration at the hands of the management and is even looked upon as a necessary evil in some cases, and secondly, it is, in many cases, eventually left to the tender mercies of cheap, inexperienced help, even if a start has been made with a good man in charge. After a year or more of operation with outside service a business man will rarely install a plant, it being the consensus of opinion that the investment would earn larger dividends if put into the business. Furthermore, with central station service, the manager is free to devote his entire time and attention to promoting the business and can rest assured that his power requirements are being taken care of by experts in production and supply of that commodity. Even if conditions should develop during the period of central station operation that make it desirable to install a plant later, the data collected during that period would permit of a much more economically designed plant than would have been possible if it had been installed in the first instance, and the owner would reap the benefit as long as the plant was left in.

Internal combustion engines, which are recommended by

Mr. Moses for industrial plants having no steam requirements, have not given the expected satisfaction in any installation with which I am familiar in this country. The cost of fuel is assuredly low, but it is not sufficient to offset the low maintenance, simplicity and reliability inherent in central station service. Where attempts have been made to approach the conditions guaranteed by the public utility companies, the comparision is no longer favorable to this type of engine.

The requirements of an office building or hotel can be so closely estimated and vary so little from year to year that an economical isolated plant can be more readily designed in such instances than is the case in manufacturing establishments. In spite of this, however, some of the principal office buildings, hotels and department stores in St. Louis use central station service. One of the hotels, which has had central station service from the outset, has a connected load of 400 kw., and the power plant of one of the department stores, which later changed to central station service, consisted of one 250-kw. and three 200-kw. units. I should like to know how the cost of operating the building mentioned under the heading "Effect of Interdependence on General Design," would have been affected by the use of an electrically driven refrigerating and ice-making plant and a low-pressure boiler. There is no question but that the cooking can be done successfully with low-pressure steam, 15 lb. or less, although this has been doubted in some quarters. From what I can gather of the conditions outlined, the building in question could be more economically operated in St. Louis by the central station than would be possible by running an isolated plant.

A fact that is often lost sight of is that practically every city taxes the gross revenue of the public utility companies and as a result is enabled to keep the taxes much lower than would otherwise be possible. Other things being equal, every public-spirited citizen should award business to the central station for this reason, if for no other.

Clarence P. Fowler (by letter): The general superiority of electrical energy for industrial lighting and power service over all other forms of illumination and mechanical transmission has been so thoroughly discussed as not to need further comment here. Having once settled upon the use of electrical energy for an industrial establishment, the first question for consideration is: Shall such electrical energy be of the "home-made" variety or shall it be furnished from the lines of a central station? In other words, is the existence of an isolated power plant for industrial uses justifiable, under average conditions, where efficient central station service is available? I am inclined to think that a careful consideration of all factors in most instances would point to a negative answer to this question. There exist several clear-cut advantages of central station service, which, it would seem, in the majority of cases entirely preclude the commercial advisability of the establishment of a private industrial power plant.

So far as I am aware, previous discussion concerning this matter has related chiefly to the cost of manufacturing a kilowatt-hour with an isolated plant, as compared with the actual price per kilowatt-hour as charged by the central station. While in many instances even so incomplete and inequitable a comparison between isolated plant and central station service may favor the use of the latter, it would seem that in order to make a fair comparison, additional advantages of central station service, which are frequently lost sight of, should have consideration. While some of these advantages of central station service to the power user are not always apparent and cannot always be exactly evaluated in dollars and cents, they are, however, none the less real.

Some of the advantages of central station service which may have considerable monetary value and which may, therefore, be properly regarded as effective in reducing the actual charge made for such service, may be briefly summarized as follows:

The modern progressive central station sells more to its customers than raw material, mere kilowatt-hours. In the purchase price of energy is included the finished product, efficient illumination and power service. In other words, the service of the up-to-date central station with its corps of trained specialists does not stop at the consumer's meter, but extends beyond to the customer's side. The central station of to-day solves the customer's illumination problems in the most efficient way and furnishes advice, gratis, as to the most advantageous methods of grouping his shop equipment and motor applications. The intelligent solution of these and other industrial problems is now well recognized as an important factor in accomplishment of the maximum output of labor and equipment at a minimum of operating expense. As the specialized knowledge necessary to render such advice is not possessed by the average industrial plant manager or superintendent, it is evident that if he would arrange his plant for the greatest operating efficiency it would cost him a certain amount for the engineering supervision, advice, etc., necessary to bring about such an arrangement, under isolated plant conditions.

Industrial corporations are primarily interested in the manufacture and sale of some particular product of a certain quality, at a minimum of cost, and with such corporations the question of power is merely incidental and more or less of a side issue and it is only natural to expect that the most satisfactory solution of power and lighting problems can best be left to the management of the central station, which makes a specialty of the manufacture, application and sale of electrical energy, in the same way that industrial corporations are specialists in the manufacture, uses and sale of their respective products. By the adoption of central station service, therefore, all the advantages of specialization are preserved on both sides. The lack of this specialized knowledge, necessary for the most efficient operation of isolated plants, is strikingly brought to the front by Mr. Moses in his reference to the unsatisfactory operating conditions he has found prevalent in such plants. Taking only one of the different items which he mentions in this connection, namely, the wide range of practise which he finds in a matter so important as the purchase of coal, it is but typical of the usual leaks and lack of efficient management and system in the operation of isolated power plants. To properly systematize and continually supervise the operating methods of isolated plants may cost an amount which would be considerably more than the value of the economies secured thereby, in the case of small isolated plants, and may also amount to no inconsiderable sum in the case of larger plants. These added costs, should, of course, be charged against the cost of power production on the premises.

In passing, it should be noted that the use of central station service also permits the executive heads of industrial corporations to be relieved of the effort and annoyance of supervising the operation of a private power plant. The time and attention that managers of industrial plants would find it necessary to devote to the production of "home-made" energy could, when purchasing central station service, be given over, with better results, to concentrating their energies on increased sales, cheaper production or increased output.

Another point which may frequently favor the use of purchased energy, particularly in the establishing of new industrial enterprises, a point which I believe central station sales policies have not brought sufficiently to the fore, relates to the advantages to be secured to owners of an industrial undertaking by the investment of an amount that otherwise would be required for the construction and equipment of an isolated power plant in manufacturing plant proper, thereby increasing the output by obtaining a maximum of productive equipment for a given expenditure of capital. A notable example of this came to my attention not so long ago. The plant in question was a textile mill and had available for its construction a certain definite sum of money, 12½ per cent of which would have been necessary for the establishment of its own power plant. After carefully considering the power question it was decided to purchase energy of the central station, with the result that the annual output was increased by nearly 15 per cent through the investment in productive manufacturing plant of an amount equivalent to that which would have been required for the construction of an isolated power plant.

In order roughly to estimate what advantages might have resulted, under average conditions, if central station energy had been adopted instead of isolated plants and if the construction cost of the latter had been invested in productive manufacturing plant, in the case of eleven selected industries in the United

States, the following table has been prepared. The figures given in this tabulation are for the year 1905 and are either directly taken or estimated from a combination of statistics found in Bulletins Nos. 57 and 88 of the U. S. Bureau of Census, relating respectively to manufactures and to power employed in the same. Referring to this table, the figures given in columns *A* to *E* inclusive are taken directly from the Government records, just referred to, while the values in columns *F* to *N* inclusive are estimated, from figures given in columns *A* to *E* inclusive, in the following manner: column *F* gives the estimated amount of capital at present invested in isolated power plants, for the industries represented, and in order to be conservative was figured at the average cost of $65 per rated horse power employed, as found in column *D*. This figure is considered fair in view of the mixed character of the motive power used. Having ascertained the estimated capital invested in isolated plants, the estimated capital employed in productive manufacturing plant exclusive of power plant is given in column *G*, and is obtained by deducting the former quantity given in column *F* from the total invested capital as found in column *C*. Column *H* gives the net estimated return on capital invested in manufacturing plant, exclusive of isolated power plant, and is derived from the total value of products, and operating expenses, as given in the census bulletins previously referred to, an allowance being made for depreciation in each case. By dividing the total of the products given in column *B* by the number of thousands of dollars of capital invested in productive manufacturing plant proper as given in column *G*, the figures in column *I* are derived, which show the estimated value of products for each $1,000 invested in productive manufacturing plant proper. By considering the amounts in column *F* (representing isolated plant construction costs) as invested in productive manufacturing plant proper, and applying the unit figures given in column *I*, the various estimated increases in the value of products, as given in column *J*, are obtained. Column *K* contains the values given in column *J* expressed as percentages of the total value of products given in column *B*. By applying the percentages of net return on capital invested in productive manufacturing plant, as given in column *H*, to the estimated amounts invested in isolated power plants as given in column *F*, the net return on such, if employed in productive manufacturing, is ascertained, and is given in column *L*. Column *M* gives the estimated number of horse power that may be considered as continuously active throughout a year of 8760 hours. Finally, column *N* gives the estimated maximum average increase in price for each used horse power per year that various industries could afford to pay for purchased energy above the cost of isolated plant service, before exceeding the profit that would result from investing isolated power plant construction costs in productive manufacturing plant proper.

So much for the compilation and derivation of the figures used.

Upon glancing through the table some interesting points develop. It will be noted from column *D* that by far the most important industry of those considered, in the matter of aggregate rated horse power, is the iron and steel industry, and that this same industry is second in rated horse power per $1,000 of products, while the greatest such unit recorded is that for the paper and wood pulp industry, with nearly six horse power per $1,000 of products, the silk industry being the lowest in this respect, with hardly more than one-half horse power per $1,000 of products.

The final values given in column *N*, showing the estimated average margin that industrial plants of various types may allow between the cost of " home-made " and purchased energy, may at first sight seem to show rather erratic tendencies in the wide numerical range scheduled, but when it is remembered that these figures are susceptible to a number of modifying factors, peculiar to each industry, the seeming discrepancy is explained. For example, let us consider the two extremes shown in column *N*, the cotton goods industry, with the lowest margin of $8 per used horse power per year, and the lumber and timber products industry, which shows the greatest margin of $93 per used horsepower per year. Considering the former, it will be seen from the table that the cotton goods industry shows the least net return on the invested capital and this, coupled with the fact that the rated horse power requirements of this industry are not very large, results in a low earning power of isolated plant cost when invested in productive manufacturing plant. Reviewing the conditions responsible for the abnormally high figure of $93 margin in the case of lumber and timber products, from an inspection of the table it will be clear that while the rated horsepower requirement per $1,000 of products is practically the same for this industry as the figure for the cotton goods industry, the chief reason for the large margin in the former is found in the large net return on investment in productive manufacturing plant, coupled with the relatively small continuous use of rated horse power employed. In the iron and steel industry, while the rated horse power per $1,000 of products is second in order of importance, the low net return on the invested capital militates against a greater margin between the cost of purchased and " home-made " energy, the actual figure being $18 per used horse power per year, as given in column *N*, and while this figure is of substantial proportions it is noteworthy that it is next to the lowest in the list of industries considered. It is further notable that even the minimum figure given in column *N* is quite material and, while only averages are dealt with, the results arrived at in the table are strongly indicative of the importance, to those laying out new industrial undertakings, of carefully considering the imminent possibilities of increased outputs and resulting profits to be had through the investment of all available funds in productive manufacturing plant, made possible by the purchase of all electrical energy required from an outside cen-

tralized source, with an organization capable of intelligently handling energy supply problems with a maximum of advantage to the consumer.

Surely the advantages of central station service as enumerated above may have a monetary value, which may be such as to often render the net cost of such service very low when all the factors are given due weight. It is therefore apparent that the mere gross price per kilowatt-hour charged by a central station may be of secondary importance and is not always the controlling element in making a comparison between " home-made " and purchased energy.

P. R. Moses: In reply to a criticism of the diagrams of practise, the diagrams speak for themselves. They were not intended to " determine relative proportions " of " apparatus." They were designed as finger posts to point out the mutual dependence of the parts of the mechanical and electrical equipment of buildings and to show that with certain basic conditions, certain types of users and makers of steam and electricity would seem to be, *prima facie*, advisable.

How can it be an open question, economically speaking, whether it is advisable to install steam-driven fans for indirect heating, when steam must be supplied for heating, in any event, and when it can be obtained from the exhaust of the engine driving the fan, thus doing two jobs instead of one?

As to the statement " that low efficiency and wasteful lighting is regarded as an element which does not disturb the overall efficiency of the isolated plant "—this is a fact which can hardly be disputed if the amount of steam at low temperature (215 deg. fahr. or less) required for heating, drying or evaporation processes is more than the amount which would be supplied by the wasteful engines operating the isolated plant. If we have to fill a reservoir from a water power at the rate of a thousand gallons a minute, and we put a waterwheel in the flow, if we only need the power available from 500 gallons a minute there could be no gain by installing a high-efficiency waterwheel. The same thing holds true of isolated plants, and it is rather surprising to have this questioned.

Curve 12 is typical of an office building *with* a restaurant and curve thirteen of an office building *without* a restaurant. This I believe was clearly shown in the original paper and the two curves were chosen particularly to show the effect of occupancy upon load. It is interesting to note that in the Trinity building the all-day load factor was only 37.6 per cent of the capacity of the sets under steam. It was to aid in avoiding such errors as this that the paper was presented, and it was hoped that other data of operation results would be presented showing average, maximum and night loads, which would aid future designers in planning their equipment to secure at least 75 per cent load factor at all times for sets operating. The paper sets forth clearly the reason for not including elevator swings, because in modern plants these swings should be taken care of by a storage battery unless they are of such minor importance as to be carried by overload capacity. The criticism of the log sheets is beside the mark, as the paper clearly states that they were inserted merely to show sample *forms*.

Mr. Parker's discussion brings forth several points of interest and his suggestion that the data on building heating be reduced to a formula is an excellent one.

I have found, however, from experience, that a comparison of buildings similar in size, character, occupancy and location is more useful than attempting to derive the cost from a formula. One building may have textile manufacturing requiring little heat and another a series of studios requiring a lot of heat, one may be open twenty-four hours a day and another nine. Formulas could be derived to cover all cases, but the comparative method seems easier.

The discussion of installation costs per kilowatt capacity is based on an erroneous idea of the intent of this table. The costs given were intended merely to aid designers in preliminary estimates of costs, hence the items of cost of building and stack did not enter. Frequently these items must be considered, usually as an increment to the general cost—that is, the stack would be required anyway, but may have to be larger. Engine and boiler rooms will be needed but might be less extensive without a plant than with one. This is by no means always true, but sometimes.

The point about the reduced effect of marginal increase or decrease in production is well taken, and the facts stated have been strikingly borne out by the records of operating results in a number of plants where increased kilowatt-hour output resulted in a very much lower ratio of increase in fuel use.

The interesting discussion of the comparative saving derived from the use of tungsten light on central station and isolated plant service shows a saving nine times as great when using central station service as when using isolated plant service.

I cannot agree with Mr. Parker that this does not prove the corollary to be true, viz., that isolated plant service costs one-ninth as much as central station service under the conditions noted *for all increments of load*. That is, given a plant operating under stated conditions, additional load can be supplied at a comparatively slight increase in cost up to the limit of the plant capacity, because the increase in cost is confined to the costs of fuel and oil, and, even in these items, in a greatly decreased ratio.

The discussion by Mr. Martin requires no comment, except that it seems difficult to understand what repairs to heating system have to do with cost per kilowatt-hour. The item of depreciation seems confused with the item of repairs, otherwise it is hard to see how the neglect of the item of depreciation " well nigh resulted in the total shut-down of one of our largest office buildings."

As to Mr. Nichols' discussion, the statement in the original paper is quite correct, that if electricity is made on the premises the exhaust steam available points to an exhaust steam operated refrigerating plant. Whenever electricity is made on the premises, exhaust steam will be available from steam-driven house, boiler and other pumps, besides those of the refrigerating plant; and where this exhaust is not sufficient and the refrigerating plant work, is a large proportion of the total work, it would probably pay to design one of the electric units to operate a sufficiently high back-pressure to do the required refrigerating work, because as long as all the temperature range and heat units are fully utilized it does not matter how much is used in making electricity and how much in refrigeration. The over-all efficiency will be a maximum.

Referring to one criticism, the emphasis was laid on compactness and simplicity in connection with the discussion of the design, and the original paper clearly points to the fact that the chief advantage gained by these two qualities is reliability.

The criticism is made that " while the figures are represented, from the heading under which they appear, as being fuel and labor costs for heating, they actually cover, in at least fifty per cent of the cases cited, by the author's own admission, the cost of producing steam for other purposes than heating the building." The author clearly stated that these costs included steam for other purposes, and his intention was to present facts and figures representing actual conditions which could be compared with actual conditions in other installations.

Manufacturing buildings frequently—one might almost say generally—need steam for manufacturing. Of what use for comparison or estimate is a cost of heating only? The whole basic condition is changed at once and for intelligent estimate another building containing similar basic conditions must be used.

Mr. John W. Lieb, Jr., brings out a point of interest in a clear and direct manner. He considers that the author's practise, as described in the paper, of using steam pumps, etc., in buildings where electricity is purchased, is not logical or justifiable.

The reason for the use of steam pumps, etc., is that in all the buildings where they are used there is a certain minimum amount of steam required all the year for hot-water heating, dryers and in some cases for refrigeration. The steam can be most efficiently supplied by first using it for pumping and it is for this reason that steam pumps and steam-driven ventilating fans are employed. Boilers, it is true, must be operated at somewhat higher pressure than for heating purposes only, but it will be found that where an attempt is made to operate one boiler for heating a building, heating water, laundry dryers and other low-temperature work, the result is invariably unsatisfactory because not only are different initial pressures required for these different purposes, but, what is of greater moment, the terminal pressures at the outlets of the various steam-using parts of the plant are unequal, and all kinds of troubles result from the backing up of one set of returns into another.

Mr. Clarkson's discussion touches on one evil in isolated plant design—the installation of engines, etc., far too large for their work, " to take care of future possibilities." How much better to plan to care for the immediate future with a reasonable allowance for future expansion and leave space for additional apparatus as the demand increases. His note of the tendency of consulting engineers to plan for possible future installation of a plant is interesting. Frequently this is the best plan to adopt, particularly in city buildings, if the renting and character of tenancy is not assured. If space is provided and if such apparatus and piping as is installed is planned with a future plant in view the present omission is often the most advisable course to adopt.

I cannot agree with Mr. Clarkson as to internal combustion engines. Their performance when correctly designed and installed is remarkably good. They not only give excellent results under test—1¾ lb. of coal per kw-hr. is not unusual with engines of less than 300 h.p.—but what is far more important, their average operating record varies but little from their test performance. My confidence in their performance was such as to justify a recommendation of the installation of three 200-kw. producer gas engine driven dynamos in far-off Porto Rico, where the ordinary labor is not our skilled type, and the results have justified fully the advice.

The cost of operation of the building mentioned in the paper would have been seriously increased by the substitution of an electric-driven refrigerating plant and a low-pressure boiler for heating and cooking. The cost of electricity for the 15-ton refrigerating plant operating about 6500 hours a year would have amounted to over $4,000 a year, and the labor required would not have been decreased $500 a year and the fuel not over $1,500, so that the annual operating cost would have been increased $2,000 and the fuel cost would have been greater.

Mr. Clarence P. Fowler's discussion re-states many of the points first developed in Mr. Parker's paper* before the A. I. E. E. on Industrial Power, and is an exceedingly able plea for the use of central station service. I do not feel that a discussion of the comparative merits of central station and isolated plant service is in order, and in fact this subject has been exhaustively treated heretofore. The suggestion that the user of electricity who is also the purchaser from the central station should leave his problems to the central station is interesting, as it reverses the tried adage of *caveat emptor*—" let the buyer beware."

The lack of specialized knowledge in the design and operation of isolated plants is a great drawback and the fact that not a single figure or record of any value whatever has been added in the discussion of the paper indicates clearly the reason.

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* *Comments on Fixed Costs in Industrial Power Plants*, by John C. Parker, TRANSACTIONS A.I.E.E., 1911, XXX, I, p. 637.

Engineers apparently have no data of operating results to give or else they regard them as knowledge which is so precious and so hard to gain as to be worthy of protection behind triple bars of steel. Why can we not have full discussion of operating results and presentation of the facts of isolated plant operating data on the heating of buildings? Hundreds of engineers throughout the country have these facts and yet they will not bring them forth.

Why? Because they are afraid that, where not controlled by uniform Public Service regulations, their figures will be used and a price fixed by the central station companies below their cost and *below the average cost of making and distributing the current.*

The supervising of private plants by the executive head of an industrial corporation mentioned in Mr. Fowler's discussion is a bogie. The extra supervision involved because of the electric generating plant is not to be separated from the supervision of the heating, and a compressing plant.

The really great argument in favor of central station service is ably developed by Mr. Fowler. It is the familiar cry of the old-time department store, " Cash." Wellington in his classical book on " The Location of Railways " says, " No expenditure, otherwise justifiable, is proper if it jeopardize the success of an enterprise as a whole." So it is with the question of installing a private plant or constructing a building or any part of a sales process which can be done without.

If the cash capital or credit is so limited that it will suffice only for a selling force then it is unwise to invest any capital in manufacturing. If the capital is sufficient to buy a manufacturing equipment but not a factory then it is unwise to erect a building —much better lease one until the enterprise is established. So, if a manufacturer has barely enough money and credit to allow him to complete his factory and start his selling then the best thing he can do is either to use the credit of the central station company, even if he pays excessive interest on the cost of the electric plant in the shape of excessive cost of current, or take the alternative which is now possible. He can purchase his power plant on the instalment plan, avoiding the necessity of taking the capital out of his business.

When he buys a power plant on this basis, giving notes and mortgage on the plant as security, he only pays the legal rate of interest and can use his cash capital and his bank credit in his business. The whole argument that the power plant cost could be better used in the purchaser's business is of no real substance. The interesting statistical table given by Mr. Fowler fails to be of value because its premise is unsound, that a purchaser must either take money out of his business or buy central station service. In fact, he frequently does neither.

I have reserved my closure on Mr. Williams' discussion of the paper to the last. Mr. Williams' discussion should be carefully considered. The admitted figures of one of the buildings on

Fifth Avenue, New York City, he states, show that " a gross annual saving of about $11,500 was effected," of which the consulting engineer received one-third. The saving was $11,500 out of a total cost of central station service of about $19,000 for the original building and one afterward supplied from it, a saving of about 60 per cent. The consulting engineer—I regret to make this statement but it is necessary for a clear understanding—only gets his one-third because he invested three-eighths of the cost of the installation.

To the consumption of current in the original building was added that of the building afterward supplied from it, but this would not have effected a saving, as Mr. Williams puts it, of $3,000 a year. The saving, even under the inequitable rate-making method based on quantitative use alone, would have been only $1,500. *En passant*, the absurdity of such a basis for rate making may be noted, although not germane to the subject—here are two buildings with nothing changed except that there is one contract instead of two, and, presto! the cost drops $1,500 a year, or nearly 10 per cent.

The plant did not cost $30,000, as Mr. Williams stated. It cost about $22,000, including all changes, installation of a storage battery, water weigher, CO_2 recorder, etc., so even allowing 15 per cent the difference is *not* " automatically and immediately wiped out."

Mr. Williams then makes the surprising statement that the whole investment in plant should be wiped out " the first year " and he adds that he does not think this premise can be fairly questioned—nor do I. The assumption is really too startling and its best answer is its own re-statement. However, the plant is still running and earning 60 per cent and will probably do better next year.

Mr. Williams next refers to the Equitable fire and forgot to mention that the supposed cause of the fire was the *lighting of the gas*, because the private plant was not being operated in the early morning, and the lighting supply was being obtained from a central station.

The criticism with which Mr. Williams closes his discussion—the reference to the omission of costs of excavation, etc.—is sometimes, but not often, well founded. Usually, space is left in a well-designed building for possible installation of a private power plant or other machinery impossible to foresee at the time of erection, and the installation of the engine and dynamos does not involve additional expense, hence it should not be charged to the private plant. In other cases this is not true, and in such instances—as where a vault has been especially opened under a sidewalk—the whole cost should be, and usually is, charged.

I cannot follow the example of the twelve-story and the eighteen-story building, but I do know of one twelve-story office building where an isolated plant reduced operating expenses nearly $4000 a year and earned over 30 per cent on its cost.

A paper presented at the Pittsfield Section Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., January 18, 1912.

CENTRAL STATION ELECTRIC POWER FOR RAILROAD OPERATION

BY FREDERICK DARLINGTON

Every engineering operation seeks to accomplish some practical result, which is measured by its financial worth or capacity to earn money by saving labor in doing something useful. There are no exceptions to this, but in railroad work, which is the subject of this paper, we often have to look further and deeper for the full measure of worth, than is usual in any other matters with which I am familiar.

In the manufacture of cloth, for instance, the problem is simple, that is, make cloth of a desirable quality, at a minimum cost; likewise in making steel rails or bricks or paper, or any article of merchandise, there is a definite result to be attained and the final test of different methods is the cost and value of the product, which in such instances is readily determined. There is no such simple way to judge the merits of transportation work for it is far more complex than manufacturing or other lines of production. This is seen in the great diversity of rates and classifications under which railroad accommodations are sold. In freight business, for example, there are different rates for long hauls and for short hauls, for car loads and for part car loads and various classifications almost without limit. This diversity has not, as many people suppose, resulted primarily from a desire on the part of railroads to " charge what the traffic will bear," but rather from necessity caused by differences in transportation costs, combined with differences in the value of services rendered. It is not necessary to enlarge upon this, for we all know it would be fatal to the interests of both buyers and sellers of transportation to attempt to make a uniform rate for all freight transportation on a ton-mile basis, or on a uniform basis of distance hauled, or on any direct measure of transportation. An equitable rate for carrying a ton of wheat from Chicago to New York City has very little relation to an equitable rate for carrying a ton of wheat twenty miles from a farm to a grain elevator; likewise, there is very little relation between the cost per ton of transporting a carload of wheat and the cost on a single ton in a part carload lot, and short hauls and part carload lots may be quite as important in the aggregate as long hauls. What I want to bring out is not the value of the work done by the railroads, immense and necessary as it is, but rather to point out the need for still more and different railroad facilities, and to show that the use of electric power from central station plants will benefit railroads and at the same time benefit all other operations requiring power.

There is a wide field for improvement in railroad service that can be best accomplished with electric power, especially for local transportation. The statement has been made that the money expended in hauling freight by wagon to and from freight depots of one of the largest railroad systems in New England, is greater than the gross receipts of the railroad from its freight business, and I am inclined to believe that this will apply to other American railroads. It is certain that the cost of hauling freight by wagon to and from railroads is a heavy part of freight transportation. Also in passenger service the collection and distribution of passengers to and from railroad depots is a matter of large cost and has an important bearing on travel. This is evidenced by the work of electric interurban trolley roads, the favorite field of which is in the territory tributary to steam railroads, where they have in many places greatly facilitated the local collection and distribution of traffic. I will not enlarge upon this for it is well understood.

In comparing steam and electric power for railroads, the comparison should not be based on the relative cost of operating certain trains by steam and by electric motive power, but the comparison should be made between the best use of steam power considering the cost and value of the service rendered, compared with the best use of electric power, considering the cost and value of electric service. It follows from the wide difference in the nature of the two kinds of power, that the train weights, schedules, etc., and even the locations that are best for railroads employing steam power, will not always be best for electric power.

So far as distribution of power is concerned, independent of whether it is for railroads or for other purposes, it is demonstrated that wherever a large number of small powers are to be supplied in a limited territory it is more economical to distribute it by electricity than by any other known method. An example is seen in the case of textile mills, where power from steam engines or waterpowers was formerly generated at each mill and conveyed to various rooms and machines by series of shafts and belts. This plan has been widely superseded with electric drive whereby electricity is generated in a central plant supplying numerous mills and is used to operate motors for driving small groups of machines in each mill, or even for driving a separate motor for each machine. Likewise, in railroad work, electric motive power enables a profitable service to be rendered with greatly subdivided motive power suitable for light and frequent trains that, if operated by steam power, would be too costly to be profitable in such small units. So it has been in every field where electric power has been extensively applied. The most important result has not been a cheapening of work that was previously accomplished by other means, but more and better work has been accomplished, and so it will be with the use of electricity on railroads and this betterment will not be confined to railroading, because there is an interdependence in electric power operations, whereby any extension of electric lines and increased use of electric power for any purpose, leads to development of more and better electric power for all other purposes. How this must always result can be predicted by using a little justifiable imagination to clear the point of view of natural bias in favor of present conditions and methods that have gradually become unfavorable for present needs.

Custom and habit often leads to the continued use of apparatus and methods for work that could be better met by new means. To appreciate this, imagine that a wholly new country, that is destined by natural resources to become rich and prosperous, is to be opened up, settled and developed, and that some empire builder with a master hand and complete foresight could furnish the transportation and power facilities of the country. By means of electricity and the railroads, he could direct the development of the country. First of all, by building railroads with electric motive power, he would at once provide the means of transportation that is always adopted where the population is sufficiently dense. Following such lines of convenient transportation and power, population centers and settlements will naturally locate on the railroads with transmission lines along the roads; these various centers are tied together, forming the most efficient power system. If a country is to have a density of population and prosperity that would pay for transportation by electric roads, then the railroads should unquestionably be provided with transmission lines connecting the cities and these same transmission lines carrying electric power along the railroads, make the most economical means for distributing power for every purpose, and all the street cars, house lighting circuits, shops and factories along the railroad would naturally derive their power from these lines, and towns and manufacturing centers are always attracted by convenient power, as well as by good transportation conveniences. Then again, a diversified and extended use of electric power within any area increases the size of the power plants employed therein and accordingly reduces the cost of each unit of power generated.

A manager acting for a central power plant desiring to sell power to a city electric railroad system, recently put the matter as follows: To the banker president of the railroad, who has a reputation of being difficult to convince in any such matters as sacrificing or setting aside part of his property, the manager said " Do you want to make a dollar?" To which, after the way of bankers, he answered, " Yes." Then the manager asked him if he " would share the dollar with someone else who helped make it," to which he answered, " yes, if he could not make it all himself." Then said the manager, " I will sell you power for your railroad at less than it costs you to make it, and even so, I can make a profit on it, for you are making it in 2000-kw. units and I am making it in 6000-kw. units, and, therefore, at less cost than you are; but besides making it in larger quantities than you are, I am serving a great variety of companies and secure a more even and steady load than you do, since you are making power for only one kind of service, namely, to operate an electric railroad; but in addition to these reasons, I want your business, because with your load added to my present load I can generate power in 8000-kw. units, and still further reduce my kilowatt-hour cost."

It is not a matter of opinion but of accomplishment that available central station power is a valuable asset to every prosperous settlement, just as are railroads and telegraph and telephone systems. As power machinery and methods of work that are not now adapted to the electric plant are becoming obsolete or wearing out they are being supplanted by electric machinery, and electricity is being installed in new works where foresight is exercised to realize the maximum benefit by centralization and unification of power.

Much that was sought by railroads long before electric motive power was available for their needs is now accomplished with electricity. Years ago Wellington in his standard book entitled " Railroad Location "—a book by the way, that deserves a much more comprehensive title—pointed out that " In the sale of transportation, the price that the consumer is able and willing to pay is greatly affected by trifling differences of convenience." He emphasizes the importance of convenient local transportation facilities and says that " The loss to the railroad due to not supplying the best facilities might be borne if it meant simply a reduction of transportation tax upon the traveler or the shipper of freight," (in other words, less money paid to the railroad,) but he asks, " How stands it with the traveler or shipper? They save indeed the two or three cents per mile, which the railway loses, but they have to pay the entire cost of cartage on their freight and pay for their own conveyance besides suffering the annoyance and inconvenience, which they estimate at a good round sum." He says, " From poor transportation facilities, the loss is threefold: The cost to the public is greater. The receipts to the railroad are less. The traffic is decreased in volume." To quote still from Wellington, " This means from the point of view of political economy, and as a plain statement of fact, which would appear in census statistics, that the capital of the country and the world is less than it otherwise would be."

We can now add to Wellington's list of losses and state that poor transportation when resulting from failure of railroads to employ electric power under conditions favorable to its use will cause a fourfold loss, including the three losses enumerated and adding a fourth, represented by the added cost of power both for railroad working and for industrial uses, and in the fourth instance, as in the three enumerated by Wellington, this means from the point of view of political economy, a loss to all—to the railroads and to the public alike.

While it has been one of the works of electric railroads to produce added values with better transportation facilities, it is not my intention to reiterate arguments for better local service with electric power as a means of increasing values. It is rather the purpose to accept the evidence of interurban railroads that electric power is advantageous for light and frequent train service, and from this premise to examine the conditions for its further application.

The general statements thus far made concerning central power supply and railroad operation are all capable of verification by examining specific conditions, but, as I indicated at the commencement of this paper, a complete analysis to apply to all conditions is most complex. It will be possible for me to give here only a few results based on actual operations which may be used by those interested as a basis to compute what economy centralization and unification of power supply will secure at other places.

The figures given below are for the cost of producing electric power in steam plants carrying railroad loads under conditions that are widely prevailing in the United States. These figures are not exact costs taken from any particular power plant, but are average costs worked out from actual results in several steam plants on heavy railroad and other work, so shown as to permit easy analysis for varying conditions of load and for different fuel costs, etc.

	Total cost per year	Cost per year per kw. of plant capacity	Per kw-hr.
Operating labor......................	$52,500	$2.10	0.100
Operating materials (exclusive of fuel)	15,000	0.60	0.025
Labor for maintenance of plant......	15,000	0.60	0.025
Material for maintenance of plant......	17,500	0.70	0.030
Total cost of power plant, operation and maintenance, exclusive of coal per yr..	$100,000	$4.00	0.180
Add the cost of coal at $1 per ton for coal of 13,500 B.t.u. per pound......	82,500	3.30	0.15
Note:—The fuel cost will increase as the cost per ton increases or the quality falls off.........................			
Other expenses pertaining to power plant operation, such as administration, legal and general expenses...............	10,500	0.42	0.02
	$193,000	$7.72	0.35
Add for fixed charges on the cost of power plant.....................	225,000	9.00	0.41
Total cost of power per yr. with coal at $1 per ton and a load factor 25 per cent.............................	$418,000	$16.72	0.76

The figures given are the cost, including fixed charges, of producing power in a 25,000-kw. steam-turbine plant, containing five main units of 5000-kw. nominal capacity each, but capable of carrying 50 per cent overload or more in emergencies.

The yearly production of power is assumed at 55,000,000 kw-hr. or a load factor of 25 per cent on a maximum load of 25,000 kw., which is the total nominal capacity of the five generators. It is equivalent to an average operation of all of the generators for 2200 hours per year at their rated capacity.

Such is the cost of electric power generation by steam for heavy railroad operation and general central station service.

There are two factors in the foregoing costs which are liable to maximum variations, viz., the cost of fuel and the average load on the plant, or as it is called, the load factor. The assumed maximum load of 25,000 kw. could easily be carried on four ordinary 5000-kw. nominal capacity steam-turbine generators, and leave one spare unit in a five-unit station. At 25 per cent load factor as assumed above (25,000 kw. maximum load and 55,000,000 kw-hr. per year), the result in thermal efficiency would be about 8.4 per cent. It is difficult to determine from actual results just what the thermal efficiency would be at other load factors, but as it is sometimes necessary to know this as a basis for arriving at the fuel costs under varying load conditions, the following approximate figures are given for these variations. The coal is assumed to contain 13,500 B.t.u. per lb.

Yearly load factor (ratio of maximum load to average output)	Average operation per yr., hours	Thermal efficiency of plant	Cost of coal per kw-hr. at $1.00 per short ton
10 per cent.	876	6.5 per cent.	0.20 cent
20 " "	1752	7.8 " "	0.16 "
25 " "	2190	8.4 " "	0.15 "
30 " "	2628	9 " "	0.14 "
40 " "	3500	9.8 " "	0.13 "
45 " "	3940	10.1 " "	0.125 "

It would be difficult to demonstrate in detail the economies that can be derived from combination of mixed power service from the above plant compared with power for only one industry like railroads, and an attempt at it would lead back to the same generalities that I have already stated, but analysis of the schedules of costs and thermal efficiencies for a 25,000-kw. plant, working at 25 per cent load factor, proves the broad assertion that in power generation large stations carrying mixed loads afford the maximum economies. Take, for example, the cost of general expenses and of fixed charges and of power station labor and material, exclusive of coal. These things are little affected by the load factor, but even in so large a station as 25,000 kw. they amount to $13.42 per kilowatt per year, out of a total cost of power of $16.72 per kilowatt per year, with good coal at $1.00 per ton, or $20.02 with coal at $2.00 per ton, etc. Furthermore, even the fuel cost per unit of power generated will ordinarily be less in mixed service plants than on plants for railroad work only, since the former generally work at better load factors than the latter. The better load factor comes from serving a diversity of operations. Also with more operations the plant will be larger, and for this reason, as well, it naturally has a better load factor and all unit costs are correspondingly less.

There are other important advantages from centralization of power in large power plants, which will have important bearing on the future of central station business, for industrial and for railroad power. One of these has to do with obsolescence, and its importance in this connection does not always receive the attention that it deserves. Another is the utilization of off-peak or secondary power, which so far has been very little realized but which will increase in importance.

Obsolescence has long been the bugbear of electric companies that are striving to earn dividends, and centralization of power seems to be their best means of salvation. We all know that electric companies that were started fifteen or more years ago, whether they were for lighting or for railroads, or for whatever purpose, have found a large part of the cost of conducting their business has been due to the failure of apparatus to meet growing demands, not so much because it was worn out as because it became obsolete, when increasing business required larger powers and improved machinery.

Good serviceable power plants became obsolete because they could not do the increasing work of later years, and were discarded because the use of power increased. Centralized power plants meet changing conditions because they are built for larger service and constructed on a unit plan that can be economically extended to meet growing demands.

The utilization of off-peak power will be promoted by the concentration at central points of large amounts of off-peak power, which can be more readily utilized as second-class power than the same amount of off-peak power if scattered through a number of small generating plants.

There are several very promising methods in prospect for utilizing off-peak or secondary power when it is concentrated in large blocks, but it is not within the scope of this paper to go into a discussion of them.

Next, turn to the power transmission side of the problem. In this the results in favor of large mixed operations are even more striking than in power generation. It is a difficult subject to generalize on, but briefly, suppose that a central plant is located at a favorable point at a coal mine or a water power, and it is desired to transmit power from the plant. It often pays to run 100 miles of transmission line to pick up a large load, whereas for a small load the cost of 10 miles of transmission may easily be too great. It follows that if the aggregate amount of power surrounding the power center is not large, it will not pay to go far for it, and the economical distribution area may be restricted to a radius of 10 miles or less. But on the other hand, if the aggregate is large, long-distance transmission will pay and the combination of large amounts of power per mile of transmission on long transmission lines, covering large areas, gives a big connected central station load. In this lies one of the great advantages in favor of including railroad roads on central plants, viz., where the amount of power and lighting scattered through a territory for manufacturing and similar purposes is not sufficient to make it economical to install electric transmission for this alone and where the railroad business is not sufficient to pay to transmit for railroad power alone, transmission for the combined loads will often be highly profitable.

There is a well-known power transmission company that affords an excellent example of the advantage of combining as much power as possible in a given territory. Its business aggregates something like 60,000 h.p., connected on several hundred miles of transmission lines, and the yearly cost of transmission, including all fixed charges and operation and maintenance of the transmission system, amounts to about $12.00 per h.p. per year, based on its peak load of 50,000 h.p. Its load is industrial power and lighting with a few street railways. In the same territory there is a total consumption of power, exclusive of steam railroads, of approximately 225,000 h.p. which, if all served from a single central power plant, would produce a maximum load of probably 150,000 to 175,000 h.p., but for various reasons, one of which is the use of exhaust steam for heating buildings, factories, etc., the maximum load that it would be profitable to serve from the central plant would probably give peaks of only about 100,000 to 120,000 h.p., exclusive of steam railroad operation. The yearly cost of power transmission, including all fixed charges on transmission lines, for serving 100,000 h.p. in this territory instead of 50,000 h.p. maximum as now served, is estimated at $730,000 total or $7.30 per h.p. per year as compared with $12.00 per h.p., which is the cost of power transmission and distribution for 50,000 h.p. only.

An examination of the steam railroad traffic in the same territory indicates that if all of the railroads used electric motive power exclusively, the railroad load would require a generating capacity of between 200,000 and 300,000 h.p., and if only the railroad lines carrying heavy traffic and frequent train service were electrified in the territory, the maximum load if served from a central station would be somewhere between 150,000 and 200,000 h.p., and that the yearly load factor of this railroad load, including freight and switching and passenger service, would be between 40 and 50 per cent. It is clear that if this load were added to the industrial and lighting load, it would greatly facilitate and cheapen the unit cost of distributing power from the central station.

In conclusion, I want to review briefly what the substitution of electric motive power for steam on existing railroads should include. It is not enough to say that it would require the construction of central station generating plants, of transmission and distribution lines, generally following the railroads, and of electric locomotives to replace steam. These would all have to be provided, of course, but that is not nearly all that should be done. Unless we look beyond such facts we cannot even appreciate the problem before us, much less solve it. When the railroads are paralleled by transmission lines over which central stations supply electric power for their operations, then the country traversed by the railroads will be in electric power zones, where power for any purpose may be taken from the lines along each railroad right of way and these lines will connect large central stations together, so that transmission lines will network the country as railroads now do and will connect important centers for power, as railroads do for transportation. Into this network of transmission circuits central electric plants will pump energy that can be drawn off in just the right amount to supply the needs of each point included in the network.

When this is carried out, the distribution of power, which is the greatest problem in the way of almost universal use of central station electric power, will be overcome with the resulting economy in generation as well as in distribution, since the most economical conditions for both generation and distribution are where large amounts of power are supplied at the best load factor attainable, which results when the largest number of operations are supplied from a single system. Thus there are many places where railroad electrification will be profitable, as outlined, where it would not pay to build transmission lines for the railroad load alone or for the industrial power and lighting without the railroad load.

Going to the single-phase substations, unquestionably these should be without attendants, which means self-cooled units. Self-cooled units within the last few years have been developed so that there would be no trouble in providing transformers of 1500 to 3000 kv-a., and I think we could take about 2000 kv-a. as the size that would be ordered under present conditions. With 64,000 kv-a. to be transformed, we would have 32 units. The cost of these was taken at $4 per kv-a. I at first considered this too high. However, on second thought, considering that the transformers are self-cooled and that it has only been by very recent developments that we have gone up to such sizes, it is probable that $4 as compared with the $2.50 is an approximate figure.

Mr. Hobart pointed out the fact that three-phase units are cheaper than single phase. That may be taken wrongly, and I wish to say that a three-phase unit of the same capacity will cost some 15 per cent more than a single-phase, but three single-phase units having the same aggregate capacity as one three-phase unit will probably cost 10 to 15 per cent more than one three-phase unit. Then there is the question of voltage. On the three-phase and d-c. system, we have 30,000 for the high-tension line. The secondary would be in the neighborhood of 800 to 1000, depending on whether the direct current was 1200 or 1500 volts. On the other hand the single-phase would be 11,000 in all probability. At first thought the 11,000-volt secondaries would cost more than the 1000-volt, and I believe Mr. Hobart so stated, but I doubt if the cost would be more in the large units that we are considering, like 2000 kv-a., and I believe that the 11,000-volt secondary would be perhaps 3 to 5 per cent cheaper than the lower voltage, due to the very heavy current on such large capacities. I will close with one other comment. The last point brought out in Mr. Hobart's paper refers to the development of the static converter or rectifier. I wish to point out from a transformer standpoint the fact that the employment of static rectifiers would permit the use of 60 cycles, as he has stated, rather than 25 cycles. If this is accomplished, and the rectifier is developed to a stage where it can be used for such work, and 60 cycles is adopted, I wish to point out that the transformers would be some 15 to 20 per cent cheaper than those quoted in the paper, which are 25-cycle transformers. In other words, that change in frequency will allow of 15 to 20 per cent saving in the transformers. This is a considerable item.

C. M. Green: What is the comparative efficiency of the two?

W. C. Smith: Before answering that I would like to get an idea from Mr. Hobart as to my assumption that the three-phase synchronous converter stations would be about the same capacity as the single-phase.

H. M. Hobart: It is my opinion that the greater drop in the line with alternating current, owing largely to skin effect in the rails, and the desirability from the operating standpoint, of cutting the line up into sections would make it well to have numerous substations. I do not see why you should forego that advantage in the number of single-phase substations, even though you have 11,000 volts. The system will comprise a great many route miles and I hardly think it would be expedient for a railway with the *very dense traffic* considered in this paper, not to be able to cut up its line into as small sections as, at most, ten miles, whatever system is used.

C. M. Green: Do I understand you to mean ten miles from the station or place the station in the middle?

H. M. Hobart: I mean along the line of the railway. I think you would want to divide that up into ten mile stations anyway for a line with such heavy traffic as that with which my paper deals.

W. C. Smith: I mentioned the fact that three-phase transformers would cost less than single-phase transformers of the same aggregate capacity. It is also true that at the present time they would probably be more efficient; so that, choosing arbitrarily the three-phase at 8000 and single phase at 4000 kv-a., the probabilities are that the efficiencies would be about the same in the two systems. I think that would amount to a small consideration.

B. A. Behrend: I have consistently refrained in the past from expressing my personal opinion on the merits or demerits of the single-phase system as such, or of any particular part of the single-phase system, as the generating station, the transformer station, the substations, locomotives, etc. Perhaps few men have been so privileged as myself in obtaining an insight into the operation and also the construction and design, as well as cost and the waste of thought, labor and money expended in single-phase electrification, as I have, but I have resisted the great temptation for the last seven years in particular and for the last twenty years in general, to air my views in public. Mr. Hobart's judicial paper, treating this subject in a manner which takes it out of the range of polemics, allows me to express my opinion without compromising myself or the large manufacturing institutions with which I used to be connected for a great many years.

First allow me to express my entire agreement with Mr. Hobart's results. I believe he has stated these very fairly as to the cost of the generating stations. I believe his statement is not quite correct that units for three-phase current generation of 15,000 or 16,000 kw. at 1500 rev. per min. represent the limit at that particular speed. I myself worked out a year and a half ago a 25,000 kw. unit which, if it should ever be built, I have not the slightest hesitation in saying would be successful, and within the conservative guarantees as to temperature rise which it is now customary to make. I believe Mr. Hobart has given us an excellent summary, and after saying this, allow me to make a few critical remarks.

My criticism first of all is this, that the paper deals with but one-half of the problem, and unfortunately the least important half. The generating station, electric generators, transformers and the line, to my mind, are a mere bagatelle in comparison with the problem at the other end, the locomotive, etc. The problem of operating your locomotives successfully after you have built them is more important. Mr. Hobart's paper is distinctly analytic and analyzes the problem up to the critical point —the locomotive. The method of analysis is distinctly orthodox. The single-phase system has come into large use. I designed some single-phase generators in 1892, and my master designed some 22 years ago, which are still in operation. Mr. Hobart knows of one large successful single-phase power plant at Frankfort on the Main, built in 1892. We must take a heterodox view if we are to look at the single-phase system from the right angle. We must go back on the rules of standardization of the American Institute of Electrical Engineers. We must forget temperature rises as measured by thermometers. We must forget a great many things about electric generators and motors. Unless we do so, unless we turn heterodox, viewing this whole problem from a practical angle, we cannot understand the single-phase system, why it came and why it has done such wonderful good to the electrical engineering industry. I say we must become heterodox. Why? First take the generators—they are very large. Mr. Hobart is right in regard to his diagram only to some extent. Mr. Hobart shows two machines at 4000 kw. I would substitute one of 8000, which would reduce our cost a little. We should obtain a somewhat greater simplicity, which is quite essential. That is a minor matter, however, and does not enter into our argument, because the cost of the power station would be only 10 per cent greater. We must not figure in hundreds when our investment is in millions, and the money a railroad has to invest in a problem is not measured by the cost of the power house. Let your power house be twice as expensive and it will be still all right, if the operation of the locomotives and everything else were ideal; so I say we must be heterodox. We must size up the whole situation and view it not only as the power station—not important alone—or the locomotives—not important alone—but we must take the whole problem and view it as a unit. If the power house breaks down because the electric generators are not designed properly or because some important things are overlooked, very well, change it, and you may be able to obtain a successful generation of power. Let me assure you that after a great many trials and a great many mistakes one of the large corporations in this country engaged in the manufacturing of machinery, succeeded in making the New Haven road a success. I hold no brief for this company or for the New Haven road, but I do want to reiterate that the success of that single-phase power transmission from Woodlawn to Stamford has been a landmark in the engineering business.

Now the next step in the solution of the problem is how can you simplify it—how can you eliminate sources of trouble. Reliability is the whole thing. This must be capitalized—it should be expressed in figures. You cannot do it, but let me assure you that any experienced banker, in trying to form an opinion as to whether his client's funds should be placed in any enterprise, first of all looks not at the financial standing but at the personnel connected with the enterprise. It is the personnel that counts. In regard to this railroad problem, it is the reliability of your railroad, of your electrification problem, which counts in the end, and that cannot be expressed in figures.

The last pages of the paper touch a question of polemics again, the problem of single-phase railways. As I have said, I hold no brief for single-phase railways. I am expressing my opinion for what it is worth. My opinion is that the single-phase system has a field and that the d-c. system has a field; and I have held that opinion for 20 years. The essential point is that both these systems have a field, and let us acknowledge those fields. Let us have the decency to say that a system is all right under certain conditions, but is all wrong under other conditions. Let us remember that 1500 volts for railway purposes has not been tried out thoroughly. I built a number of those high voltage d-c. systems that operate today, with commutators worn fantastically—but still going and delivering current—and therefore I believe that the development of the two systems will be side by side to some extent. The single-phase system, if all the kinks are taken out, which I hope will happen in the end, will have its place. Whether it was properly applied in the case of the New Haven road I do not know. I would like to ask Mr. Hobart whether he would not be so good as to give us his own personal views of the single-phase system, taking the whole system together, for trunk line electrification? I personally do not believe I shall live to see many trunk lines operated by electricity, because it will take such an enormous amount of money that I fear it will be a long time before the railroads can make the purchasers willing to defray the expense of these electric problems.

H. M. Hobart: I do not see why we should use electricity where steam is better. I think the continuous-current system has its field, the single-phase has its field, and steam its field. Electrical transmission is appropriate where you can get a reasonable load factor. Where you cannot, there are other and more simple methods. These other methods may comprise the use of electric motors to drive the axles, and still not be electrical in the sense of transmitting electricity from a stationary generating plant to a moving train. I cannot recommend the continuous current system for all cases. It was in 1910 that I mentioned this in discussing a paper entitled "The Economics of Railway Electrification" read before the Institution of Mechanical Engineers, and which advocated the 1500-volt, continuous-electricity system for a road a hundred miles long, with one train per hour in each direction, a stop every three miles and a scheduled speed of 33 miles per hour. In my contribution to the discussion I stated that for this road the single phase system would be cheaper than the continuous, and that *steam would be cheaper than either*. I gave quantitative calculations in support of my contention. These will be found on pages 1239 to 1245 of the *Proceedings* of the Institution of Mechanical Engineers (London), for 1910.

C. M. Green: It is my purpose to speak of one very small section of this important subject, which we have before us for discussion, and that is the replacement of the synchronous converter by the mercury arc rectifier. I have had the good fortune for the past six years to be associated with the development of the rectifier for series arc lighting up to 9000 volts, 4 amperes, and on multiple work up to 350 volts, 40 to 50 amperes. The growth of the rectifier has been phenomenal, and I consider the future brighter than the past. The reliability of service is of the first and utmost importance, and the life of rectifier tubes and their service varies all the way from absolutely nothing up to over 14,000 hours, and I should be very much disappointed if in five years from now there will not be some tubes which have run over 25,000 hours, and inside of ten years I predict that we shall have tubes in service over 30,000 hours. Seven years ago tomorrow I had the privilege of running 60 kw. (10,000 volts and 6 amperes load) of electrical energy on a single tube, 25,000 volts alternating current across the anodes of the tube. The load for the tube was very excessive, however it did not give out during the short run. Since that time I have seen very much larger currents rectified with lower voltages. I have seen tests run up as high as 1000 amperes and over 1000 volts, but not at that amperage. Frankly speaking, I expect to see the mercury arc rectifier replacing the synchronous converter for 600 and 1200-volt service for railway and other work. It of course means a considerable amount of development and patience on the part of some of the operating companies in order that this result may be accomplished. You can readily appreciate that experimentally the tests must necessarily be of comparatively short duration for the simple reason that the amount of energy required is large, and when consumed on water-barrel or resistance load it runs into dollars with great rapidity so that after comparatively short tests it will be necessary to put the apparatus out into commercial service where some use may be made of the rectified energy. This furthermore has the advantage that under these conditions the rectifier is performing useful work and the expense of operating it is almost forgotten.

A Member: About what power factor would you expect to get with a mercury arc rectifier of large capacity on the alternating-current supply?

C. M. Green: I should be very much disappointed if we could not readily obtain on a three-phase supply a power factor of at least 95 per cent. However, the question of power factor depends very largely upon the transformer design and other constants of the rectifier, wave distortion, etc. On single-phase rectifiers for series arc lighting which requires a certain amount of reactance and resistance or impedance in the circuit for successful operation, 65 per cent is about the highest power factor which is obtainable, or an apparent efficiency of approximately 60 per cent, or an actual efficiency of from 90 to 92 per cent on 50-light sets, and above. The power factor for this apparatus is determined almost entirely by the load which it is required to operate. In other words, the situation is more or less similar to operating an arc lamp from a direct-current multiple circuit, 110 volts at terminals of lamp, about 80 volts at the arc and about 72.6 per cent efficiency. Some designs of series rectifiers give a very bad wave distortion of the primary.

Multiple rectifiers for the charging of storage batteries are also limited in a certain respect with reference to the power factor. In other words, if the apparatus is designed for too high a power factor, as the battery is charged the voltage across the terminals of the battery rises and the current falls off very rapidly; the set drops out and the service is unsatisfactory.

Rectifiers to replace synchronous converters would not, to the best of my knowledge, have any of the above limitations, and I believe apparatus could be designed to give a power factor on the alternating-current side somewhat above 95 per cent.

Dugald C. Jackson: I wish to express the interest and satisfaction which Mr. Hobart's presentation of his subject has given to me. With respect to the conclusions, I imagine that with equally reliable data equally well founded on practise, one could come to conclusions which would vary considerably from his, and yet the final result perhaps would be very little different as between the cost of delivering power at a certain point by three-phase generator with converter stations on the one hand and single-phase generator and transformers on the other hand. But when we look at the problem of electric lighting, or electric transmission of power and its distribution, or the special problem of the electrical utilization of power which comes into the railway problem, we must recognize that the question of delivering the power is not the final criterion. The question of making the power available for its purpose in the most satisfactory manner for the least reasonable expense is the final criterion, and the consequence is that while the old war of the alternating current versus the direct current which was waged with great vigor and some acrimony many years ago in the electric lighting field has recently seemed to break forth again in the electric railway field, that phase of the argument does not fairly represent the question before electrical engineers. The question is what will give us motive power for the railway, industrial power for the factory, or service for the electric light that is needed respectively, in the most satisfactory manner for the most reasonable expense. It has long since been settled for industrial and electric lighting affairs that the direct current has many advantages and the alternating current also has many advantages—sometimes single-phase and sometimes three-phase; neither can occupy the whole field; and I am thoroughly convinced that the same thing will be worked out for the railways. I have already expressed my opinion on that matter before the Institute, especially at the 1911 convention in the discussion of similar papers.

Mr. Behrend is a pessimist in regard to his age in years; I will admit that he is an old man measured in accomplishments, but I believe he will live to see many trunk roads electrified and I therefore must take a certain amount of opposition to his standpoint. In respect to the accomplishments that have been heretofore brought about by the alternating current in the field of electrical transmission of power I can fully agree with him.

A. E. Kennelly: It is a comfort to find a paper on such a complicated subject as this without having to indulge in speculation as to what may have been in the author's mind. The old controversy of the direct versus the alternating current is still with us, and it will be a sad day when it disappears. I look forward to the continuance of that discussion with ever new delight. This particular paper is only on one aspect of it, but it is a very important and practical aspect; and I think the conclusions which are brought out here are a surprise to a great many. We shall hope that an equally strong paper may be written on the other side and we shall enjoy hearing the contest continued over that; but whatever may be said in regard to the exact figures of three-phase versus single-phase power delivered, whatever may be the exact numerical ratio in a particular case, this at least is evident; that Mr. Hobart's paper is a plea for eliminating the stray power, I mean reactive power. Here are cases where the station applies a certain amount of effective power to a track and to a railroad, but in the one case a very large amount of reactive power is supplied which is not utilized, that is in the single-phase case, whereas in the three-phase case very little stray power is generated; and this paper is really a plea for eliminating the extravagance and the incidental cost of that stray power. The discrepancies between the size of the units two to one, the size of the conductors and the size of the various elements of the conducting system are partly due to the fact that there is spare power, unutilized power, in the single-phase system. It carries around one-third for luck and for reserve, being out of use. Of course that is a certain advantage, but it is expensive in size, first cost, etc., but in addition to that there is a very large amount of power that is not being utilized. If we remember, we are all familiar with the fact that on 80 per cent power factor for every kilowatt you deliver usefully you are also generating three-fourths of a kilowatt that is not being utilized at all, and is simply filling up the machine and utilizing the plant without being dissipated. Three quarters of a kilowatt goes into the magnetic field of the system, into the motor and other parts of the system, and is stored there for a quarter of a cycle, and then comes back in the generator. It is as though in a large steam engine there were auxiliary elements in the plant that required to be fed with a great deal of steam and its heat was dissipated and it came back again into the engine. Of course the boilers would have to supply the engine and also supply the steam necessary for this circuitous auxiliary power. The single-phasers are supplying not only the effective energy that is being utilized for driving the thrust, but they are also creating a lot of energy that is oscillating to and fro in the circuit; and this paper is an indication of the misfortune and the extravagance of that procedure. At the present time that misfortune lies with us, because we cannot bring our power factors on this kind of motor above 75 per cent, whereas with the aid of the converter and the three-phase apparatus it is possible to run nearly 100 per cent; but if this single-phase motor system should eliminate this extravagant oscillation of power which is not being utilized but acts as storage power for a hundredth part of a second, the greater part of this difference between the apparent cost and the final cost would disappear; and if we do not owe Mr. Hobart a vote of thanks for the masterly way in which he presented this subject, we certainly do owe him a vote of thanks for his dissertation upon low power factor and reactive power.

C. T. Mosman: In reading over Mr. Hobart's paper the principal thing that impressed me was the fact that he appeared to be trying to make the strongest possible case for the single-phase, whereas I had always supposed that his sympathies were the other way. There seemed to be many little items where he might have squeezed the single-phase system a little harder, but he lets it get by. The other point I want to mention is that I have heard several people comment that it would be so much better if he had continued and given us the whole story. There is one point in his paper that seemed to me rather extravagant and that was the figure of $20,000 a mile for line construction, which I understood covered the steel tower transmission line. I cannot say that I have had experience on these things at all, but I should think that $20,000 a mile would come pretty near covering all the construction along the right of way for the delivery of power to the cars. It would seem large enough for that. To me it seems very high for a transmission line. Another point is that 30,000 volts would seem very low in figuring out the amount of copper necessary to transmit the amount of power he is considering. I would like to have him speak a few words as to why 60,000 volts would not be a lot better and there would be saved a good deal of investment. I made just a rough estimate that it was three times too high and that you could build the line for nearer $7,000 a mile; and I was surprised that instead of getting 18 per cent in favor of the single-phase I got 18.5 per cent, so it did not seem to make very much difference and I I was considerably disappointed. Coal at $2 a ton struck me as being very low. I had an idea that coal in this neighborhood would cost between $3 and $3.50 at the fire door and my previous impression was that even near the mouth of the mine you probably could not get coal for much less than $1.50 and perhaps a little more at the furnace door. So I would be very much interested in having Mr. Hobart say where $2 a ton applies for first class coal. Outside of these minor points it seems to me the paper is very well taken and although this part of the discussion as applied to railways generally may be a mere bagatelle, it is the particular bagatelle that Mr. Hobart was after and he seems to have found it.

H. M. Hobart: Mr. Smith was quite right in correcting me and pointing out that there probably would not be much choice between the cost of large transformers whether supplied with 11,000-volt secondaries or with 1000-volt secondaries. High pressure does not always mean greater cost in transformer construction. An exceedingly low pressure transformer in big sizes is one of the most difficult things you can undertake. I probably did not make myself quite clear on pp. 136 and 137 in discussing the static rectifier and the advantage of 60 cycles. The case is not quite as good as it seems at first sight. As has been pointed out, there is a certain power factor loss there and you have to have your windings proportioned more liberally in consequence. Certain subsidiary windings must also be provided. Probably the transformers for static rectifiers at 60 cycles would cost nearly as much as transformers for synchronous converters at 25 cycles. If you could employ 60-cycle synchronous converters you would make a gain, because 60-cycle transformers would be lighter and cheaper, but if you substitute static rectifiers, you would introduce difficulties in power factor which offset part of the gain. But the net advantage in lower first cost and greater efficiency of the substation will nevertheless be very great.

C. M. Green: I doubt if you would go up over 5 per cent. There would still be a little advantage in the 60 cycles.

H. M. Hobart: Coming to Mr. Behrend's remarks, I did not mean to imply that 16,000 kv-a. was an utterly impracticable size for a 1500 rev. per min., 25-cycle, three-phase generator, but I intended rather to state my opinion that in the present state of the art, it would not be the best engineering to employ such generators, as they are in the developmental stage. Consequently I took 8000 kv-a. and 1500 rev. per min. as a conservative upper limit. I wanted to employ six generating sets in the station. I then pointed out that the single-phase machine if it was in one generator, would be equivalent in size to a 16,000 kv-a. three-phase machine. I should not consider it approved engineering, at the present stage of development to employ 16,000 kv-a. generators for 1500 rev. per min.

B. A. Behrend: There are a number of 15,000-kw. 1500- rev. per min. generators in operation now, and I do not know that it would be impossible to build within reasonable temperature limits 25,000 kw. at this speed.

H. M. Hobart: Nevertheless it is not sound engineering to base comparisons on the very uppermost limits that have ever been employed. I was pleased to have Mr. Behrend refer to the great skill, ingenuity and hard work that has been put into the development of the single-phase system. I fully believe that there is a field for single-phase, but that most of the work that has been done has been misapplied effort; well meant but on the wrong track. There is a sort of fatality about the single-phase system. In several of the systems for which it has been put forward, there does not appear to be much of a case for electric transmission to the train. I fully agree with Prof. Jackson that all systems are useful, and it is just exactly that standpoint which I felt ought to be upheld as distinguished from staking everything on one system, whether single-phase, three-phase, or continuous electricity. Dr. Kennelly emphasizes the point that the bad features are not so much due to its being single-phase as due to its being 75 per cent power factor. That is where the greatest disadvantage comes in. If the power factor of the three-phase generating and transmitting plant were 75 per cent instead of unity, the showing would be nearly as unfavorable as for single-phase. Mr. Mosman spoke of the $20,000 per mile as being too high. The transmission system would cost at least $700,000 for a scheme of this order of magnitude. The precise cost has to be settled according to just how many substations there are and just what distance away the generating station is. This, in turn would depend on the facilities for getting coal, etc. You would so locate your generating station as to minimize these costs so long as you did not sacrifice too much advantage in some other direction. I was conservative in putting the cost of fuel low, and the over-all efficiency of the generating station high, since I therein favored the single-phase system.

W. S. Murray (by letter): I have the following commentary and inquiries to make with reference to Mr. Hobart's paper:

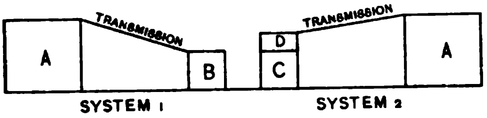
1. The title of this paper, "The Relative Costs and Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems," does not properly indicate either the scope or the object of the paper. The statements in the first and last paragraphs with reference to the "single-phase railway system" and the continuous current system more clearly bring out the motive of the author.

The attempt of the author to disqualify the single-phase system for railway electrification is so evident throughout the paper that all who read it must take this object for the subject rather than the title given by the author. I consider an explanation is due from Mr. Hobart for this inconsistency.

2. Since the object of the paper is to discuss electric operation of railroads, why does Mr. Hobart stop at the substation? Note the table of efficiencies he has presented for the two systems. On the three-phase side the chain stops at the substation. Is there no line loss on the d-c. distribution system? Wireless transmissions have made great progress of late, but I doubt their practical application in such a case as this. Again, why throw in the step-up and step-down transformers on the single-phase side? Just because they are on the three-phase? Or because it balances the table, thus making four items for each table? As a practical example, they are not used in the case of the single-phase electrification of the New Haven road. Why charge up 8 per cent on line losses for the single-phase side, when, for example, our commercial experience allows a loss less than half that amount as the total average loss between generators and locomotives.

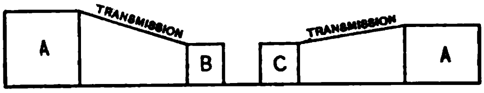
3. In the history of engineering, can any one point to the method Mr. Hobart has used to show the relation between the efficiencies of two systems—starting at the power house and working toward the railroad? I am glad he stopped at the substation, for had he arrived at the driving wheels of the train, which by the way would have something to do with the schedule, his explanations would indeed have been impossible.

Mr. Hobart starts with 160,000,000 kw-hr. per annum as the outputs of the two stations. Now it is manifestly clear that unless the efficiencies of the two systems are identical from the generators to the driving wheels of the train, if one system provides the tractive effort necessary, the other will generate either too much or not enough power, depending on whether the efficiency of the second system is respectively greater or less than the first system. A graphical example of this is as follows:



In the above figure, *A* in both systems 1 and 2 represents the output of the station. *B* represents the amount of power that must be delivered to the drivers of the trains, and thus system 1 provides the exact amount needed. System 2, having higher efficiency than system 1, not only provides enough power $C = B$ for the railroad, but has left over an amount *D* (not needed). I believe this simple diagram will make clear the error Mr. Hobart has made in starting toward the driving wheels from the power house, rather than vice-versa.

Let us reverse the direction now and work from the tractive effort requirements to the generating station, still adhering to our simple diagram:



$B = C$ again represents the power requirements of the railroad. Both systems supply the exact amount required, but now note the difference in output between the two stations; the A of system 2 no longer equals the A of system 1.

If, to produce an equal tractive effort, a system employing a chain of higher transmission efficiencies requires less output than another, is it fair to compare transmission efficiencies starting with equal outputs from each station? I think it is only necessary for me to point out this erroneous assumption to make clear the fact that the deductions must be equally erroneous.

Before leaving the question of transmission efficiencies, let us look at a table that has associated with it the facts of actual practise, and this time, following the plan as outlined in Fig. 2, we will trace the power requirements in the two systems from the driving wheels to the steam turbines, starting with—say 100,000,000 kw-hr. as the necessary driving-wheel power.

Three-phase d.c.			Single-Phase.	
Kw-hr. per annum	Per cent efficiency	Items	Per cent. efficiency	Kw-hr. per annum
100,000,000		Drivers.		100,000,000
116,150,000	86	Loco. motors.	84	119,050,000
		Loco. transformers.	96.7	123,150,000
120,400,000	96.7	Loco. resistances.		
132,100,000	91	D-c. line.		
141,400,000	93.5	Synchronous converters.		
145,000,000	97.5	Step-down transformers.		
149,800,000	97	High-tension a-c. line.	97	127,000,000
153,750,000	97.4	Generators.	95.8	132,700,000
		Turbines.		
		$\frac{132{,}700{,}000}{153{,}750{,}000}$ = 86.6 per cent.		
		$\frac{153{,}750{,}000}{132{,}700{,}000}$ = 1.16 per cent.		

or 16 per cent more power for the three-phase d-c. system.

Thus it is apparent that *for the same tractive effort developed in the driving wheels of the trains* the number of kilowatt-hours to be generated in the single-phase power station is 86.6 per cent of the three-phase station, or, stated in another way, the three-phase station will have to generate 16 per cent more power than the single-phase station to accomplish the same result at the *driving wheels* of the train equipment.

Having now drawn attention to the attempt to disqualify the single-phase system by this fallacious treatment of the transmission question, I wish to point out a few isolated errors in assumption and design that Mr. Hobart has made.

Let us take a look first at Mr. Hobart's 8000-kw. machine. Now just why did he select this size? It is a rather odd one. I do not recall ever having seen this size of generator in print before, and certainly not on the floor of a power station.

By a selection of this size Mr. Hobart has admittedly and erroneously assumed it will carry him out of the environment of 1500 rev. per min. for the single-phase generator, as after he has allowed for the larger capacity made necessary by the star winding *using only two legs* and increased the copper for his 75 per cent power factor conditions, he has built the unit up until it represents in three-phase capacity a generator of 16,000 kw. Of course, had Mr. Hobart allowed his generators to retain the modest capacity of 5000 kw., then his double generator single-phase unit would not have been safe.

Notwithstanding, however, Mr. Hobart has calculated without his host, for there are other manufacturers who have built 1500-rev. per min. generators, whose three-phase capacity has been 14,000 kw., and have offered tenders on machines of 20,000 kw. capacity. Thus Mr. Hobart's double generator proposition fails. Two hundred and forty tons is indeed a weighty generator to charge up for a 16,000-kw. machine, when one of 14,000 kw. has already actually been built which weighs but 95 tons.

Before leaving the generator end of things, I am forced to draw Mr. Hobart's attention to the fact that his statements concerning steam economy at high speeds is at variance with the statements his company has advanced with reference to economies at low speeds. We will grant that two generators, each of half the capacity of one, weigh more than the one generator (and we reserve the privilege of using one), but his statements as to steam economy for the type of turbine used are contradicted by other advocates of the same type of turbine. However, it is all summed up when it can be stated as a fact that the manufacturers who have been in the business of real single-phase machinery can build *one* generator in the form of a single unit, large enough and with the same speed, to match up with Mr. Hobart's single unit three-phase machine. Let us not forget, however, that Mr. Hobart will owe us either a refutation or explanation of the low economy he applies to high economy, four-pole, 750-rev. per min. Curtis turbines. Throughout his paper in text and foot-notes we are reminded constantly that he is being liberal with the single-phase. A too great liberality might do a great injustice to the three-phase. Why not be just? Say what it is, not less or more than it is. I might say Mr. Hobart showed, for instance, great liberality in choosing that 8000-kw. generator, as 240 tons of single-phase generator was a far too liberal supply.

Now having shown the error in proposing the double generators, let us have a look at some of Mr. Hobart's thoughts on generator design. It is evident that Mr. Hobart has had little to do with dampers—that is, field dampers. He tells us the loss in the dampers is just equal to the armature loss, and backs it up by quoting 13 kw. for the field damper of the single-phase generator and 13 kw. for the armature loss. Evidently Mr. Hobart has assumed that the damper has to neutralize the complete magnetic flux due to the armature turns. If it did, even then its loss would not be what he has stated. He evidently does not appreciate that the armature field is made up of two components, each revolving in opposite directions and of equal value. One of them is in synchronism with the rotor and is therefore not acted upon by the damper. The other component revolving in the opposite direction to the rotor flux is compensated for by the damper. Here, therefore, Mr. Hobart's figures are reduced to one half. Now let us go a step further: On account of the long armature connectors necessary to a two-pole winding, and the short connectors inherent to the squirrel cage wound damper, the proportion again is cut in half due to the resistance of the damper being in that proportion to the armature, and so Mr. Hobart's figures sink to 25 per cent of their value.

Still in the domain of machine design, let us discuss for a moment Mr. Hobart's views on regulation. He says "Incidentally the three-phase unity power factor installations will have some 6 to 8 per cent inherent regulation, whereas the inherent regulation of the single-phase 75 per cent power factor installation will be of the order of 15 per cent or worse, and will be thus so inferior as to require that some type of automatic regulators be provided."

Can it be possible at this late stage of generator design Mr. Hobart is not awake to the fact that an inherently poor regulation in a machine, which compared kilowatt for kilowatt with another of equal weight and better regulation, gives the best account of itself when measured on the scales of efficiency. The 6 per cent machine has no regulator, less kilowatt capacity and poor regulation. The 15 per cent machine has a regulator, more kilowatt capacity and perfect regulation. Thus the regulator pays for itself many times over. Besides this its inherent regulation is in marked economical contrast to the revolving mass of substation apparatus which the author recommends to buffet the short circuits of the line.

In conclusion, let us compare Mr. Hobart's hypothetical single-phase system with the actual single-phase system in operation on the New Haven road. He gives the single phase aggregate annual efficiency as 81 per cent thus involving a loss of 19 per cent. The aggregate loss between the steam turbines and the electric locomotives on the largest single-phase road in operation is 7 per cent; thus giving an efficiency of 93 per cent. Mr. Hobart's assumed losses are, therefore, 2½ times as great as the actual losses. Hence, there is nothing left but a choice between the theory propounded by the author in his paper and practise as we find it; which?

Edgar Knowlton (by letter): In the first part of Mr. Hobart's paper is a comparison of the weights of the three-phase 8000-kw. generator at 1500 rev. per min. and a single-phase 8000-kw. generator at 750 rev. per min. I believe that the weights of these two generators will be more nearly represented by 100 and 200 tons since this is the ratio of the three-phase ratings of the two machines and the reduction in speed will not greatly increase the weight of the single-phase machine.

A single-phase 8000-kw. 1500-rev. per min. generator is a practicable machine but, as explained above, its weight, cost, and efficiency, would vary but little from that of the same capacity machine at 750 rev. per min.

For the losses and efficiencies given a little further on I would be inclined to substitute the following:

THREE-PHASE 8000-KW., 100 PER CENT POWER FACTOR., 1500 REV. PER MIN.

Armature I^2R loss	25 kw.
Field " "	25 kw.
Core loss	115 kw.
Windage loss	100 kw.
Total loss	280 kw. (3.25 per cent)
Eff. (Excluding bearing friction)	96.75 per cent.

THREE-PHASE 6000-KW., 80 PER CENT POWER FACTOR

Armature I^2R loss	25 kw.
Field " "	40 kw.
Core loss and windage (excluding bearing friction)	215 kw.
Total loss	280 kw. (4.5 per cent)
Eff. (excluding bearing friction)	95.5 per cent.

SINGLE-PHASE 4000-KW., 75 PER CENT POWER FACTOR, 1500 REV. PER MIN.

Armature I^2R loss	17 kw.
Pole face winding I^2R loss	17 kw.
Field I^2R loss	33 kw.
Core and windage loss (excluding bearing friction)	215 kw.
Total loss	282 kw. (6.6 per cent)
Efficiency (excluding bearing friction)	93.4 per cent.

A comparison of the estimated losses is given in the following table:

	Loss	
	Estimate in the paper	Estimate as above
Three-phase, 800 kw., 100 per cent power factor, 1500 rev. per min.	2.6 per cent	3.25 per cent
Three-phase, 6000 kw., 75 per cent power factor, 1500 rev. per min.	3.5 per cent	4.5 per cent
Single-phase, 4000 kw., 75 per cent power factor, 1500 rev. per min.	5.2 per cent	6.6 per cent

The differences in the weights and losses, however, do not affect Mr. Hobart's conclusions as to the relative cost of the two systems.

John B. Sparks (by letter): Mr. Hobart's comparison between the cost of single-phase and three-phase current at the distant end of the transmission line is of considerable interest in view of the fact that both systems of generation and transmission are being adopted on the Continent for single-phase railways. While Mr. Hobart calculates single-phase current to be 9 per cent more costly at this point, the additional cost in the three-phase case of the rotary machinery required to transform to single-phase and the attendant losses practically balance this, so that there is little to choose between the two systems. In most cases indeed the all-single-phase proposition will be found strictly the most economical, but where the current may be used for power as well as for traction, generating and transmitting three-phase may be found most satisfactory.

Mr. Hobart's arguments as to the comparative size and cost of single-phase and three-phase generators are not very clear. A simple calculation shows that the three-phase rating of any machine is 1.73 times the single-phase rating (using two phases in series) on the basis of equal current density, or about 1.4 times on the basis of equal armature copper losses. The actual figures, however, obtained from a well-known Continental firm for four generators ranging from 2500 to 10,000 kw. single-phase output show an average three-phase rating of 30 per cent greater than the single-phase rating (the full-load efficiencies are only about 0.5 per cent greater and the regulation full-load to no-load 3 per cent less in the case of three-phase working). Assuming unity power factor for the three-phase machine and 0.75 power factor for the single-phase machine, the latter will weigh and cost, therefore, about 1.75 times as much as the three-phase machine of the same kilowatt output. It is not clear why Mr. Hobart has not taken the same transmission line pressures in the two cases; presumably the increased cost due to the higher single-phase pressure is covered by there being two instead of three insulators per pole. It would have been more economical to have taken a larger total copper section in the single-phase case.

It would be interesting if Mr. Hobart would complete his synthesis of the cost of current per unit by including the distribution costs and losses and stating the cost per unit at the trains. Continuous current at 600 to 1200 volts costs, he concludes, only 18 per cent more than single-phase current at from 6000 to 12,000 volts. The cost of the distribution and contact wire system in the latter case is very much greater than the cost of the distribution and third rail system for direct current working, and the cost per unit at the trains might consequently be even greater for single-phase current. In view, however, of the admitted higher cost of single-phase as compared with direct-current equipments and the higher maintenance costs in the former case, any slight superiority of the single-phase system in the cost of current supplied to the trains is of little importance.

Roger T. Smith (by letter): Incidentally the figures in Mr. Hobart's paper serve to show the advantage of the purchase of electricity for railway traction purposes wherever the railway load factor is low, and indeed other things being equal (which is seldom the case) it is a great advantage to a railway company to buy its electrical energy from a supply for general purposes, where that energy is only one item tending to increase the diversity factor of the whole supply, and to pay for it, as it is used, out of revenue, rather than to be obliged to pay interest on capital invested in a generating station which may for many years be a burden on traffic returns out of all proportions to the receipts.

Before dealing with the argument it may be of interest to refer to one or two points which in themselves do not affect the argument.

Dealing with the table of substation machine load factor and "all-year" efficiency, the figures may be compared with those of a substation supplying continuous current for the Hammersmith & City Railway forming a small item in London suburban electric railway service. The substation is equipped with La Cour motor converters and not with synchronous converters and the average power factor is never as much as 1 per cent below unity. The machines work in parallel with a battery whose input and output is controlled by automatic boosters. For 1911 the machine load factor was 63.9 per cent and the all-year efficiency 84.1 per cent including the battery and 86.6 per cent excluding the battery. Turning to the next table, the two substations supplying this railway (with only 10 miles of single track) for an annual output of 8,000,000 kw-hr. had a combined load factor of 60 per cent and cost 0.12 cents per kw-hr. for wages, oil and stores. Surely the machine load factor as defined for substation performance, is the correct load factor to use for generating station as well as substation performance. The rated output is the continuous capacity of the station and the percentage of this obtained during the hours the machines actually run alone tells the station engineer if his plant is used in the most economical way. Skilful management can increase the machine load factor while the maximum-power load factor may remain nearly stationary.

A small generating station belonging to the Great Western Railway, equipped with reciprocating engines, supplies the two substations, of which one has already been referred to, with three-phase current. It has an output of 10,000,000 kw-hr. for traction only, yet it may be interesting to give the figures corresponding to note (9) of Mr. Hobart's paper. During 1911 the average B.t.u. of the coal used was 11,900, *i.e.*, the calorific value is 3.46 kw-hr. per lb. This for 100 per cent efficiency between furnace and feeders corresponds to 0.288 lb. per kw-hr. but the actual thermal efficiency was 7.9 per cent. Comparing this generating station with that referred to in the note for the West Jersey & Seashore Railway the results for 1911 for coal of 11,900 B.t.u. are as follows:

Year	Output, traction and lighting, in million kw-hr.	Lb. of coal per kw-hr. output	Overall efficiency per cent
1911	11.8	3.65	7.9

Coming to the argument itself regarding the efficiency, from the steam turbine to the distribution system, of three-phase continuous current supply as compared with single-phase supply, the actual advantage of one over the other depends wholly on the single-phase power factor assumed. Mr. Hobart has taken this average power factor at 0.75, and while any figure given must be accepted with caution (since in the United Kingdom charges are always based on kilowatt-hours so that kilowatt-ampere hours are not metered) I think for British railways 0.75 may be unnecessarily low. There are only two single-phase railways in the United Kingdom, the Heysham-Morecambe line of the Midland Railway and the South London Suburban lines of the London, Brighton & South Coast Railway.

For the Heysham line, with an intermittent service of about twelve trains each way per day, average results are of no use since when no trains are running and the line is only charged there is a leading current. The tendency of this charging current is to raise the power factor, but the inductance of the line outweighing its capacity, the general effect of the line when trains are running is to lower the power factor. On the official trial runs the power factor of the low tension energy during a set of tests giving maximum acceleration (closely corresponding to suburban running) was 87 per cent and during a set of non-stop runs between Morecambe and Heysham (with a large percentage of coasting) the power factor was 86 per cent. Both figures will be reduced at the generating station by the inductance of step-down transformers on the train and by the line, but these were not measured. On the Brighton Railway the power factor during trial runs works out as 80 per cent but the average power factor of the generating station has not been measured. From these two results, one during the test of a service on the Midland electrified system imitating suburban traffic and the other during the test of a typical London suburban service, it would seem that Mr. Hobart's estimate of average power factor may be too low. The figure of 0.75 is to be accepted with caution and there is every probability that in some actual railways it is exceeded, while means for improving the power-factor of the whole supply are not beyond the power of the electrical engineer.

Perhaps the most interesting part of the paper is the general conclusion, where the combined use of both three-phase- continuous current and single-phase current are advocated to deal with different classes of traffic—a view first publicly ad-advanced as far as Mr. Hobart is concerned in his Royal Engineers' lecture at Chatham in 1909.

Mr. Aspinall's statement made before the Institution of Civil Engineers and quoted by Mr. Hobart puts the matter very clearly, and it may be said that there are very few railways in Great Britain and Ireland possessing a suburban service of sufficient importance to warrant electrification, in which the stopping trains do not run over roads kept entirely separate from those used by the long distance traffic. If this is not the case for the whole of the suburban traffic it certainly is so in the majority of cases. For instance the London & North Western Railway has under consideration the electrification of some 80 miles (single track) of suburban road. This is entirely distinct from its main line although the Euston and Watford electric line will run for many miles beside its main line. The system on which the company must electrify its suburban railways is settled for it by the fact that the rolling stock must run over sections already electrified on the third and fourth rail continuous current system, but it is difficult to see what possible difference this could make to the use of any other system of electrification it may choose to use on its main line should the time ever come for it to be electrified.

On the other hand there are English railways where the suburban system forms such a large portion of the whole system and is so intimately interwoven with the main line that two systems would be bad engineering. The Brighton Railway is such a case and it has chosen one system to suit all conditions.

H. M. Hobart: The plan adopted by Mr. Murray, of carrying out the tabular comparison in his discussion, is of interest and I am of the opinion that, by suitably modifying and extending the conception, instructive results may be obtained. I propose to illustrate by an example the method by which we may, in any given case, establish a comparison of the power required at the generating stations for each of the two systems under discussion.

A hypothetical railway's rolling stock comprises the equivalent of 70 trains, each train consisting of five 60-seat passenger cars, or a total of 300 seats per train.

Let the *average* service provide a schedule speed of 25 miles per hour, and let the average distance between stops be one mile. If the average duration of each stop is 20 seconds, then, since there will be 25 stops per hour, the average speed from start to stop will be

$$\frac{3600}{3600-25\times 20} \times 25.0 = 29.0 \text{ miles per hour.}$$

For good rolling stock operated over a well-constructed straight and level track, the energy required at the axles may be estimated from the formula

$$\text{Watt-hours per ton-mile} = 0.074 \times \frac{S^2}{D}$$

where S = average speed from start to stop, in miles per hour (= 29.0)

D = average distance between stops in miles (= 1.00)

Thus we have:

Energy required *at axles* = $0.074 \times \frac{29^2}{1.00} = 62$ watt-hr. per ton mile.

For such a service the overall efficiency of the electrical equipment on the train will be about 70 per cent, irrespective of whether continuous-electricity apparatus or single-phase apparatus is employed. Consequently the input *to the train* will be

$$\frac{62}{0.70} = 89 \text{ watt-hr. per ton mile.}$$

This value corresponds to the condition of test runs made with well-designed and well-constructed rolling stock over well-built straight and level track in calm weather. The conditions of actual practice may be assumed, in this hypothetical case, to increase the consumption of the train up to the gross average of 115 watt-hr. per ton mile and this value may be considered as being sufficiently liberal to allow for non-productive train movements. By methods[1] known to be correct, it can be estimated that the weight of such a 300-seat train will be:

210 American tons when the motive power is supplied by continuous-current train equipment.

270 American tons when the motive power is supplied by single-phase train equipment.

Consequently for the consumption per train we have

210 × 0.115 = 24.2 kw-hr. per train mile for the trains equipped with continuous-current apparatus and

270 × 0.115 = 31.0 kw-hr. per train mile for the trains equipped with single-phase apparatus.

Let the requirements of the service be such as to call for 50,000 miles per train per annum for each of the 70 trains. Then the total annual consumption at the trains amounts to

70 × 50,000 × 24.2 = 85,000,000 kw-hr. for the continuous current trains and

70 × 50,000 × 31.0 = 108,000,000. kw-hr. for the single-phase trains.

We may throw these results into a tabulated form similar to that preferred by Mr. Murray and may complete the calculations in the way he has outlined. This is done herewith.

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[1] These methods are explained in the author's treatise entitled "Electric Trains" and were employed and discussed at the July 1910 meetign of the Institution of Mechanical Engineers in London. Considerations of space render it inexpedient to set forth here the steps in the estimation of these train weights.

Three-phase, synchronous substation system. (Generator pressure = 11,000 volts)			Single-phase system without transformers except on train (Gen. pressure = 11,000, volts)	
Kw-hr. per annum	Per cent efficiency	Items	Per cent efficiency	Kw-hr. per annum
59,500,000	——	Drivers	——	75,500,000
85,000,000	70.0	Train equipments	70.0	108,000,000
88,500,000	96.0	Circuits from substations	——	——
97,200,000	91.0	Substations	——	——
102,000,000	95.5	High-pressure line	89.4	121,000,000
105,000,000	97.4	Generators	94.8	127,500,000

Since $\frac{127,500,000}{105,000,000} = 1.21$ we see that for the single-phase system 21 per cent more energy is required to be provided annually by the steam turbines in the generating station.

Thus for supplying the needs of the stipulated passenger service, 21 per cent more energy must be delivered annually from the power house turbines when the single-phase system is employed than when the three-phase system with synchronous substations is employed.

I am aware that the percentage at which I have arrived applies exclusively to the particular assumptions and service relating to the hypothetical case which I have studied. For a more sparse passenger service with greater average distance between stops, and for freight service the results will be less unfavorable to the single-phase system, but there is a big margin to be overcome before the 21-per cent. greater amount of energy required by the single-phase system is wiped out. I have not dealt with the far greater *capital outlay* required for single-phase rolling stock, as Mr. Murray does not mention the question of the relative capital costs of rolling stock for the two systems. Mr. Murray is wrong in employing efficiency as a criterion of merit. It is necessary to also consider the capital outlay by which that efficiency has been attained. Mr. Murray gives the efficiency of the high pressure line on the New Haven road as being 97 per cent. Obviously by trebling the outlay for line copper he could increase this efficiency to 99 per cent. But it would not be true economy to do so. The highest economy might correspond to half as much line copper, even though the efficiency is thereby decreased to 94 per cent. Presumably 97 per cent was the right value to adopt for the case he had in hand but it has no bearing whatsoever on the appropriateness or otherwise, of the line efficiencies adopted in my estimates.

In the above tabulated comparison I have left out the step-up transformers, to bring the comparison into conformity with Mr.

Murray's preferences, but it is obvious that this policy will, on extensive systems, mean resorting to several smaller generating stations instead of a very few large ones, thus involving lower load factors and also requiring the location of the generating stations at other than the most favorable sites and thus decreasing their commercial economy. I have taken the three-phase transmission line's efficiency at 95.5 per cent, the value taken in my paper, but instead of taking the single-phase line at the efficiency of 92.0 per cent which corresponds to a 15 per cent higher transmission pressure as explained in foot-note 10 of my paper, I have reduced it to 89.4 per cent the value which, as I explain in that foot-note, corresponds to the same outlay for copper as for the three-phase line and the same generator pressure of 11,000 volts. This change is also necessitated by Mr. Murray's preferences for eliminating step-up transformers.

Mr. Murray may take exception to my plan of basing my calculations upon the requirements of a single class of passenger service, but I would ask him to observe that corresponding calculations can be made for any other class of train service and that the case I have taken represents an exceedingly important one. I frankly admit that for a sparse long distance passenger service with infrequent stops, and for freight service, the case will not be so desperate a one for the single-phase system. For such a system as the New Haven, where several classes of rolling stock will be operated electrically, each class can be analyzed in accordance with the plan I have illustrated, and the aggregate taken for the road's entire equipment. For cases where the single-phase system shows up to be the most economical when both capital and operating costs are taken into consideration, that system should obviously be the one put forward. My own personal opinion is, however, that such cases will be rare. I have stated in the paper that I am of the opinion that engineers have greatly magnified any difficulties associated with the use of both systems, each dealing with its appropriate class of rolling stock. This is also, as stated in my paper, the view of Mr. J. A. F. Aspinall, general manager of the Lancashire and Yorkshire Railway, and, also as we find in this discussion, a close approximation to the view of Mr. Roger T. Smith, chief electrical engineer of the Great Western Railway. Both of these gentlemen have been responsible for many years for extensive electrified sections of main-line railway and each dissents strongly from the view that there is usually any need for using other than the most appropriate system for each class of traffic.

As regards the rest of Mr. Murray's criticisms of my paper—they are chiefly directed to suggesting that I have painted too lurid a picture of the conditions in three-phase generators when employed for providing a supply of single-phase electricity direct to railways without the interposition of substation machinery. My answer is to quote from the 1911 A.I.E.E. TRANSACTIONS, Vol. XXX, p. 1511, Mr. B. G.

Lamme's description of the single-phase generators as finally modified to withstand the conditions of operation on Mr. Murray's road.

Mr. Lamme states:

"There is one feature in connection with the generating plant which has not had its full significance brought out before. I refer to the use of 11,000-volt machines with one terminal grounded. These generators have three-phase armature windings of the star type with one of the three terminals permanently grounded. Two of the legs of the star are used for the single-phase circuit, while the third leg is used in connection with certain three-phase work. Across the railway phase the potential is regulated for 11,000 volts normal. by means of an automatic regulator in connection with the fields of the generator. The third leg gives a little higher voltage normally, due to the small load which it carries at present. In consequence, its voltage is usually somewhere between 11,000 and 12,000 volts. Assuming this at 11,000 volts, then in these machines we have an equivalent, as far as insulation stresses go, of a three-phase generator with grounded neutral *with* 11,000 *volts between the neutral and the terminals.* This therefore is practically the equivalent of *a* 19,000-*volt three-phase generator with the neutral grounded.* It is more than this, as it is the equivalent of a 19,000-volt machine with the neutral grounded and *with the terminals tied directly to* 100 *miles* of 11,000-*volt overhead system without the interposition of transformers.* This is a very abnormal condition compared with anything that is being done in this country at present. 16,500 volts is the highest generator now used on a large scale, as far as I know. But here we are actually running under conditions corresponding to 19,000 volts with the hardest kind of service and with an overhead line without transformers which is going to be extended to about 500 miles. Under these conditions the generating plant has made an extremely good record, as indicated by Mr. Murray in his table of delays due to power house. I may say that for about two years, or possibly more, there has been practically no trouble as far as the generators are concerned; that is, any trouble which would shut down the system. There has been one breakdown in one machine, but a careful examination of this one case developed no cause for the breakdown other than a damage to the insulation in originally putting the coil on the machine. There were no signs of deterioration of the insulation, and the insulating materials on the damaged coil appeared to be as sound and flexible as when first put on. So here we are running machines *at the equivalent of* 19,000 *volts on a three-phase system,* and during two years there has been continuous service. This is a most excellent record. If we compare this with a late practice, now being advocated here and there, of winding large turbo generators for low voltage, such as 2200 volts, and then stepping up to voltages, even as low as 6600 volts, we can see what a *wonderful thing* this New Haven operation is. In some cases at the present time, 11,000 volts, or even 6600 volts on the generator is being condemned as bad practice because of dangers from line voltage, surges, lightning and such things, but in this New Haven plant there are 100 miles of overhead system under conditions where it is exposed to surges of the worst sort."

In the above extract Mr. Lamme portrays far more vividly than I have done in my paper, various features in which single-phase generators supplying electricity direct to the trains are more elaborate, heavy and expensive than three-phase generators supplying substations. I stand by my figure of 240 tons for the weight of the 8000 kw., 75 per cent power factor, 25-cycle, single-phase generators. I am aware of instances in England and America where much lighter single-phase generators have been installed for railway work. I am also aware that they have been utter failures.

Mr. Roger T. Smith gives us the advantage of some carefully prepared results from his own experience. His data for the over-all efficiencies of substations and for the outlay for wages, oil and stores per kw-hr. are not quite so favorable as those in my paper, but it must be noted that I have dealt with large units. It had been my hope that my paper would serve to bring forth in the discussion a large amount of specific data from the experience of other engineers, such data, for instance, as this which Mr. Roger Smith has contributed, as also the data contributed by Mr. Knowlton and Mr. W. C. Smith. It is a most laborious task to derive such data for concrete cases, and engineers are tempted to base their conclusions on abstract reasoning. Sooner or later, however, recourse must always be had to rigorous quantitative comparisons of the commercial economies attainable by the alternative methods by which the desired results may be reached. Often this is not done till after large sums have been expended on the wrong system but it might just as well be done in the first instance. Great economies would thereby be effected and electrification propositions would command more respect from the railways.

Mr. Sparks and several other contributors to the discussion have expressed the opinion that the comparisons should have extended from the generating station to the train and should not have stopped short at the substations. I have briefly met this criticism in the section of my reply which dealt with Mr. Murray's remarks. I have dealt very thoroughly with the rolling stock end of the comparison in various contributions to British engineering societies and on these occasions, the chief criticism has been that I appeared not to realize that the grave disadvantages of single-phase rolling stock were far more than offset by the advantages of single-phase methods in all *other* parts of a railway electrification system. The results arrived at in the present paper show that the disabilities of single-phase methods extend right through the system, from and including the generators in the station, to and including the motors on the train.

A paper presented at the 269th meeting of the American Institute of Electrical Engineers, New York, March 8, 1912.

SOME PROBLEMS OF HIGH-VOLTAGE TRANSMISSIONS

BY CHARLES P. STEINMETZ

For a considerable time the voltage of long distance transmissions was limited by the line insulator. Until a few years ago, the transmission line insulator was the same pin type as used in telegraph and telephone lines, differing only by its larger size, by the replacement of glass by porcelain, and by the addition of a few more petticoats, but no radical change had occurred, until the limit of this type was reached at 30,000 to 40,000 volts—with a few 60,000-volt lines of questionable reliability.

The development of the suspension type of insulator practically removed this limitation. By breaking up the potential difference in a series of successive steps of moderate voltage, by the use of a series of insulating disks between line and ground, it became possible to insulate lines for voltages of 100,000 to 200,000 with a margin of safety greater than that of most of the 40,000-volt lines of old. In such steel tower lines with suspension insulators, even direct lightning strokes may sometimes reach the line without destroying its insulation, and the problem of line insulation thus appeared solved.

However, at extremely high voltages, even the suspension type of insulator must finally find its limitation due to the unequal voltage distribution between the successive insulating disks. With a number of equal insulating disks sharing the voltage between line and ground, the potential difference across the insulators nearest the line is higher, and the potential difference across the insulators nearest the ground is lower, than the average potential difference per insulator, the more so, the greater the number of insulator disks. Thus the flash-over voltage of a string of *n* insulator disks is not *n* times that of one disk, but less, and the more so, the greater *n*. Finally a point is reached where a further increase of the number of insulator disks does not further increase the flash-over voltage. The reason for this is that the potential difference across each insulator disk is proportional to the current which passes the insulator (as capacity current or displacement current, and as dielectric energy and leakage current—the latter negligible except in wet weather). Each insulator disk, however, carries its own capacity current plus all the capacity currents against ground of the conductors joining the insulator disks, between the insulator disk under consideration, and the ground, at their respective fractional voltage. Thus the insulator disk nearest ground carries only its own capacity current while that nearest the line carries its own capacity current plus the capacity currents against ground of the entire string of insulators, hence the latter carries a larger current, and thereby absorbs a larger potential difference. The string of insulators represents a circuit containing distributed series capacity—the capacity between the two sides of each insulator disk,— and distributed shunt capacity—the capacity of the connection between the disks, against ground. The general equations of such a circuit of distributed shunt and series capacity, applied to the multigap lightning arrester, have been given in the TRANSACTIONS.

This effect is the more marked, the higher the frequency, and may lead to the puncture of insulators at transient voltages below the normal circuit voltage.

From this it appears that the use of a large number of small insulator disks is uneconomical at very high voltages, and a few large disks of high disruptive strength preferable.

To extend the insulating possibilities of the suspension insulator type far beyond the voltages now contemplated, therefore requires a grading of the insulator disks in their capacity, so that the disk nearest the line has the highest, that nearest the ground the lowest capacity, or the addition of capacity at the surface of the insulator disks, in proportion to their distance from the ground. The capacities of the successive insulators of a series should be proportioned so that the product of the capacity and the total displacement current (against ground and across insulator) of each insulator disk is proportional to its disruptive strength.

However, this " multigap effect " of the suspension insulator type becomes of serious moment only at voltages beyond those contemplated at present.

More serious at present is, that we have reached transmission voltages at which the air begins to fail as insulator, and direct escape of electric energy into the air begins, as corona.

This is at present the most serious limitation of transmission voltages. This led to the study of the law of corona, and the investigation is still being continued. The voltage at which a serious loss of power by corona begins depends on the size of conductor, the conductor spacing and the air density.[1] In proposed high-voltage transmission lines—above 80,000 volts—an investigation of the line conditions regarding probable corona loss becomes necessary. By the use of large aluminum conductors, possibly even with separate tower lines for each phase—to get very great distance between the phase conductors—we may be able to reach a quarter million volts as transmission voltage, and possibly still higher voltages by special designs of the line conductor, of which various forms have been proposed.

With the development of the grounded steel tower line construction with suspension insulators of high disruptive strength, with the grounded overhead wires protecting the line against the entrance of severe lightning disturbances, and the aluminum cell lightning arrester protecting the stations, atmospheric lightning has practically ceased to be a formidable enemy of long distance transmission; practically complete protection against atmospheric lightning can be afforded, and where lightning disturbances damage the transmission line, the ultimate cause is usually either faulty or cheap line construction—usually the latter.

Protection against atmospheric lightning thus can not be considered any more as an engineering problem, but is rather an economic question as to how far the value of the protected apparatus, and of the continuity of service, warrants the cost of lightning protective apparatus.

At the lower transmission voltages used before the development of the suspension insulator, the line was the weakest link of the transmission system, but it was believed that transformers could be built of any size and for any voltage.

At 100,000 volts and over a phenomenon makes itself felt, especially in large transformers, which is negligible at lower voltage: the distributed capacity of the high-voltage transformer winding.

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[1] F. W. Peek, Jr., *The Law of Corona and the Dielectric Strength of Air*, TRANSACTIONS A. I. E. E., 1911, XXX, III, p. 1890.

At lower voltages, the transformer capacity is negligible, and the transformer thus an inductive apparatus, and as such impervious to all high-frequency disturbances, such as traveling waves, impulses, stationary oscillations, etc. High-frequency currents can not enter the transformer, but produce high voltage between the end turns, protection against which is given by the high insulation of the end turns of the transformer, which has been used now for some years. Or the high-frequency disturbance, originating in the line, is entirely kept away from the transformer by the interposition of an inductance—a choke coil—between line and transformer.

At very high voltage the electrostatic capacity of the transformer becomes appreciable, and the high-potential coil of the transformer then represents a circuit containing distributed capacity, inductance, resistance and conductance, just as a transmission line.

The high-potential coil of a transformer differs materially from the transmission line in its constants. In the transformer the inductance is much higher, the capacity lower, than in the transmission line; the resistance is lower, and the conductance low, though not negligible: it represents the energy component of the capacity current, and is due to the dielectric losses in the insulating material of the transformer.

The results of this difference in the constants is, that transformer oscillations are higher in voltage and lower in current, and of lesser attenuation, that is, die out at a slower rate, than line oscillations, and cumulative oscillations—that is, oscillations of increasing amplitude—are more liable to occur in transformers than in transmission lines.[2]

The high-voltage transformer thus must be considered as a circuit, capable of oscillating, just as a transmission line. That is, high-frequency oscillations may originate in the high-potential coil of the transformer, or oscillations originating in the transmission line may enter the transformer, and then, in passing over the transition point from line to transformer, increase in voltage while decreasing in current, by the transformation ratio of the transition point, as discussed in previous papers.

The danger to which a transformer is exposed by high-frequency disturbances from the transmission line, then, is not limited

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2. Oscillographic reproduction of such cumulative transformer oscillation I have given in "Electric Discharges, Waves and Impulses," page 99.

to the end turns only, but damage may be done anywhere inside of the transformer, wherever a wave crest forms—which depends on the frequency of the disturbance—and such destruction of an inside transformer coil by outside disturbances is not infrequent.

Inductance interposed between line and transformer then becomes a source of danger: while it keeps line disturbances out of the transformer, it also reflects disturbances which originate in the transformer, back into it, and thereby increases their voltage and their destructiveness. It thus becomes necessary to add to the inductance (the choke coil) a device which bypasses disturbances which come from the transformer, but does not allow line disturbances to pass into the transformer.

This leads into the field of protection against the phenomena of high-frequency disturbances, which now are the most serious, since, in the aluminum cell, a practically complete protection against transient high voltage has been developed, and which, with the increasing size of electric systems, are a constantly increasing source of danger, to high-voltage overhead transmission systems as well as underground cable systems.

In high-voltage long distance transmission lines of 150 miles or more, the capacity current of the line becomes considerable, and may, especially in 60-cycle systems, reach values higher than the full load current. Even then, however, the capacity current is not as serious as may be expected, and its main objection is, that it uses up generator capacity, that is, loads the generators with current which represents no power. Since it is due to shunted capacity, it may be compensated for by shunted inductance, that is, by connecting reactive coils of sufficient size permanently between the lines. This has frequently been proposed, and occasionally done.

Far more serious is the impairment of voltage regulation, incident to very long transmission lines. Assuming constant voltage at the generator terminals, the voltage at the receiving end of the line varies considerably between no load and full load—especially inductive load. Shunted reactance does not eliminate this, but while it reduces the no-load voltage by compensating for the capacity current and so eliminating the voltage rise due to this leading current, it lowers the full load voltage and so leaves practically the same voltage drop between no load and full load. A line of quarter wave length—800 miles with 60 cycles, 1900 miles with 25 cycles—transforms from constant potential to constant current. Hence, with constant voltage at the generator end, the voltage at the receiving end would rise to infinity at no load—that is, in practise, would be limited only by the resistance drop of the capacity current—and voltage regulation thus would be absent. Long before this condition is reached, voltage regulation is materially impaired. This phenomenon is most serious in the case of a short circuit on a system fed by the transmission, when the circuit breakers at the end of the line open; in this case the load suddenly changes from overload to no load; the turbines, relieved of their load, momentarily speed up and increase the generator voltage; the capacity current of the line reacting to magnetize the generator field still further increases the generator voltage, and as at constant generator voltage the change from full load to no load would cause a considerable voltage rise, with the increase of the generator voltage, this voltage rise at the receiving end of the line may reach 50 to 75 per cent and more. This excess voltage is not a transient voltage, but is dynamic, and thus can not be discharged by any protective device of necessarily limited energy discharge capacity, but can only be lowered by consuming power or lagging current, and even aluminum cells in this case, if not instantly relieved, are destroyed.

The most effective way of protecting against this sudden rise of dynamic voltage when the circuit breakers at the receiving end of the line open seems to be, not to open the circuit entirely, but arranging it so that an inductive load is thrown into circuit by the opening of the circuit breakers, sufficient to keep the voltage down. Various ways exist of accomplishing this result.

The long debated question, whether grounded Y or isolated Δ connection is preferable in high-voltage long distance transmission lines, seems to approach settlement in favor of isolated Δ. The isolated Δ has the advantage that a ground on one of the lines as a broken insulator, etc., does not cause a short circuit, and so permits continuing the operation of the system, thus giving greater reliability of service. However, if the ground is an arcing ground—as is usually the case—it produces a continuous high-frequency disturbance, and this is liable to destroy apparatus, often very rapidly. As a result, this advantage of the isolated Δ could usually not be realized, but it was a question between a short circuit and shut down—with grounded Y—or the possibility (or probability) of damage to apparatus and thus finally also a shut down, by the arcing ground in the isolated Δ. With the development of protective devices which immediately eliminate an arcing ground by converting it into a permanent ground[3] this objection to the isolated Δ connection was eliminated.

A problem of long distance transmission, which requires solution, is the control of branch circuits. Very often it may be desirable to supply a moderate amount of power from a high-voltage transmission line by a branch line of moderate length, and a considerable total load may be secured by such local supply from a transmission line. However, if the branch lines are connected directly to the main line, any accident in a branch line involves the entire transmission system, and the branch lines must be constructed with the same high insulation strength, and the same protective devices and controlling devices as the main line. This is economically not feasible with smaller demands of power. Equally uneconomical is the installation of a transformer substation at the branching point, for the operation of the branch line at lower voltage. This makes it desirable to develop some power limiting or localizing device at the branching point, such as would not interfere with the supply of the power demanded in the branch circuit, but would localize this circuit so that an accident, as a short circuit or ground on the branch line, would not seriously affect the main transmission system, and thereby would permit a cheaper construction of the branch line, more in correspondence with the smaller amount of power supplied by it. For this purpose a suitable form of power limiting reactance would be used.

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3. See paper by Prof. E. E. F. Creighton: *Protection of Electrical Transmission Lines*, TRANSACTIONS A. I. E. E., 1911, XXX, I, p. 257.

DISCUSSION ON "SOME PROBLEMS OF HIGH-VOLTAGE TRANSMISSIONS" (STEINMETZ) AND "CHARACTERISTICS OF PROTECTIVE RELAYS" (HEWLETT). NEW YORK, MARCH 8, 1912.

David B. Rushmore: I want to say a few words about some of the new things in power transmission. President Dunn mentioned the waterpower part of it—water is often spoken of as "white coal." We are now coming to a situation of "black water," that is, we are going beyond the development of waterpowers for power transmission, and one of the installations under consideration, which is just being put in, is one of the most interesting phases of present power transmission. The Lehigh Coal and Navigation Company, the oldest of the anthracite companies in the Pennsylvania field, is just in the process of installing the first steam station in the East for purely power transmission purposes. They are going to be within easy transmission distance of both New York and Philadelphia, and ultimately will have a steam turbine plant of 120,000 kw., as their plans are at present. In future they may exceed that capacity. Their plans are to transmit power, for local distribution largely, for cement mills at first, and also, presumably, for the lighting of the towns through which they will pass, and possibly reaching into New York or Philadelphia, or both.

There is now in process of construction on the Mississippi river at Keokuk, Iowa, a 400,000-h.p. plant to develop the water power and naturally to reach out in all directions and furnish the lighting and power for that neighborhood.

In other parts of the central west there are under actual construction at the present time a number of plants for transmitting power from coal mines, burning the coal and transmitting the power, combining in one system a large number of smaller lighting and power plants. Very soon there is to be in operation in Virginia a waterpower plant which is going to sell electric power to the Pocahontas coal field, which is a very unusual situation. There has just been placed in operation in Michigan a plant to operate at 140,000 volts, and there is under consideration, in the farther west, a plant which may operate at a very much higher voltage than that. So that power transmission at present, in the art of transmission, in the development of the anthracite fields (and I may add that the other anthracite companies are watching this development with the greatest of interest, because selling their power in that form has many attractive features, and it is not unlikely that we may have a number of other developments in this field)—in the kind, in the voltage, in the distance, the high-voltage power transmission, (not the question of high-voltage power distribution in large distribution circuits as in the Ontario hydroelectric system,) is coming more and more under consideration, and also the question which we must face at some time, the State control of power distribution, as in Ontario the State will sell power to municipalities. That borders on a question of great importance to a large number of men. Some of you know that the Ferris bill at Albany proposes to do this.

There is one gentleman at this meeting who has had very much more experience in actual power transmission work than most of the men in the Institute, having been connected with the early development in Utah of the Telluride Power Company, which was one of the earliest of the large transmission companies, and afterward he served as operating manager of the Central Colorado, and now he is in St. Louis preparing to receive a large proportion of the 400,000 h.p. which is being developed on the Mississippi at Keokuk. I refer to Mr. Ruffner, and I am sure it would be very interesting to the Institute members if he could be induced to tell something of his experience in this work.

C. S. Ruffner: The general problems of trunk transmission systems are those which are growing out of the distributing systems of lower voltage, and it seems that we must shortly face the necessity of so providing means of control and operation on large interconnected high-voltage systems of large power that those systems may be operated with the same reliability and satisfaction with which the lower voltage and lower capacity circuits have heretofore been operated.

That seems not only to be a question of degree in voltage and power concerned, but in some measure a question of the methods of connections and details of operation. Particularly, I believe that the features brought out by Mr. Hewlett's paper are the ones on which the greater part of the success of any high-voltage power system must depend.

Unfortunately the larger systems now in operation seem to have been the result of more or less gradual growth of various systems with very little harmony in their original design, which, being connected together, operated under adverse circumstances. Under these circumstances the questions of relays and control have become of the greatest importance. If such systems were possible of immediate development in their final stage, relays would be not only disadvantageous, perhaps, but a distinct nuisance, and I am sure Mr. Hewlett then would not recommend their use in general. Most of the relays I have been acquainted with have been relays installed in the hope that they might accomplish some good function and were operated either by disconnecting from the control circuit or plugging their connection by some means. That, I think, should not be taken as a criticism of the proper use of relays, but rather an expression of the belief that they have been used too indiscriminately and in places where they should not have been used. Perhaps, to counteract the impression that statement may have made, I owe it to Mr. Hewlett to say that we have used in Colorado his balanced relay, described in the paper, with excellent results, when nothing else seemed to be able to insure satisfactory service. In that case two power stations were feeding one substation from a single line each, that is, the two lines came to one point, and from that substation the lower voltage power was delivered to a synchronous system, the system including lighting service, induction motors, synchronous motors, and such apparatus as is used for general factory and residence lighting. A great deal of trouble was experienced on the transmission circuits of that plant, but after installing this equipment of relays their action was made accurate enough so that in several cases they disconnected the defective line, allowing service to be continued from the remaining good line—in one case, from a station which at the time of the occurrence had been running as a synchronous motor with no water on the waterwheel, and disconnected that defective line promptly enough and acted in partnership with the waterwheel governor so that the synchronous load was not interrupted. I think that is as much as could be asked of any relay, and it was necessary to use relays in that situation to obtain any satisfactory service at all.

There is one other feature that might be of interest, referring to the statement made in Dr. Steinmetz's paper, on the action of suspension insulators, of atmospheric disturbances being manifested particularly at the insulator closest to the transmission line wire.

I recall one system in which some two hundred cases of lightning disturbance occurred during one season. In all the cases where the disturbance affected the transmission line insulators, the disk nearest the conductor was damaged, in most of the cases punctured, and in about twenty-five per cent of the cases in which the insulators were damaged, the insulator nearest the grounded structure suffered in the ensuing arc. None of these were punctured. This shows very distinctly the effect of the high-frequency disturbances on the puncturing and failure of transmission line insulators. It indicates, apparently, that we might insulate a line too thoroughly, for ordinary purposes, and still could not obtain satisfactory service at high frequency.

I have seen a great many cases of transmission line trouble, originating in line and apparatus, and being manifested in breakdowns at different places in the circuit, but I have never yet seen a case of failure of any of the connected apparatus which did not seem to be entirely due to the localization of potential due to the point of high frequency and reactance. Perhaps that statement is a little too broad, but I can recall no occurrence of an arc, due to the failure of any apparatus, or over-voltage, which was not very clearly explained by the presence of high frequency combined with the change of circuit constants at the point of breakdown.

F. W. Peek, Jr.: I think in connection with Dr. Steinmetz's paper it is interesting to look back into the past, and then forward into the future, to see how past difficulties compare with present difficulties, how apparent limitations of the past compare with apparent limitations of the future. What makes me think of this is that the other day I came across, quite accidentally, an old book of letters by a very prominent engineer—it was not such an old book either, measured in time, but old measured by engineering progress. The writer stated in one letter that an operating transformer had actually been built that could stand 15,000 volts, and it was hoped that ultimately a transformer could be built to operate successfully at 20,000 volts.

The apparatus at that time was the limiting feature of transmission. Voltages went up by leaps and bounds, and transformers were shortly thereafter operating practically at voltages of from 50,000 to 60,000. At this stage the pin type insulator began to give trouble, so, naturally the suspension insulator was invented. Voltages then jumped up to 100,000, and another trouble appeared, or what seemed to be a trouble or limiting feature, that is, corona. This led to investigations of corona losses, and it now appears that we still have some margin in the matter of corona limit; for instance, power could be transmitted at 200,000 volts with a conductor about one inch (25 4 mm.) in diameter with 12 to 15 feet (3.6 to 4.6 m.) spacing.

With long lines and high voltages other troubles appear; as an example, suppose we take a line, say, 200 miles long, with a voltage of 140,000. The capacity current may equal the total load current of the whole station. This will mean trouble unless some method is adopted that will take care of this heavy leading current, or the generator units are properly arranged as to size. If part of the load is supplied by part of the generator units and the load is suddenly lost, these units may be over-loaded by the capacity current. Another emergency to be provided against is the rise in voltage at the receiving end (due to capacity current through reactance) when the load is suddenly thrown off. Taking a practical instance, after the comparatively small lighting load is taken on in the evening, the heavy factory loads go off; over-voltage is put on the lamps. Fortunately, the effect of capacity current can generally be well taken care of by shunted synchronous reactance.

Now, it is rather interesting, for the moment, to look forward into the future and perhaps ask a question—What will actually be the limiting voltage of power transmission, or limiting distance? Will it really be due to the loss of energy into the air by corona, the line insulator, the apparatus, or will it be an electrical feature after all? Will it not rather be, with some few exceptions, an economic or natural feature? For instance, the power naturally concentrated at a given point, as in a waterfall, will generally be exceeded by the demand before the distance becomes so great that it is necessary to use voltages above the electrical limit.

Percy H. Thomas: In the early days of power transmission the assumption was that the length of line that would be financially justifiable would limit maximum voltage, the theory being that a voltage as low as would carry the load the requisite distance should be used. At the present time, however, high voltage is required, not necessarily for long distance transmission, but for large power transmission. This high voltage serves, in some degree, to produce leading current to balance the lagging current of a general load. From this point of view you will see there is an advantage in using from 150,000 to 200,000 volts, if possible, if there are to be stations of a half million horse power. Corona losses at 200,000 volts will undoubtedly be taken care of, as have all the other difficulties that have come up in high-tension transmission work.

It has just been said that there was a time when it was questionable whether 15,000-volt transformers could be made to operate. I happen to remember a case where some 10,000-volt transformers were ordered and promised, and some were built. These were oil-insulated, but no solid insulating material was used in addition to the oil, and the transformers were found, when tested, to stand only something like one-third normal voltage, if I remember correctly. They were started up and ran at as high voltage as they would stand, and then they were taken out of the oil and examined, and then put in good shape and put in again and the voltage again applied and the transformers run a little longer. Soon a voltage as high as half normal voltage could be used before they broke down. They were examined again and found not to be injured, and were put in oil again, and after having been run thus a half-dozen times, they finally got to a point where they would operate at normal potential, 10,000 volts. They were finally taken out and put in service and did good work. It was not understood at that time that it was necessary to dry transformer oil. As they were run and operated they got hot, and with patience the tester unconsciously succeeded in getting the oil dried out. There was no harm done by the numerous breakdowns because there was no solid material between coils, and the oil space alone was relied on for insulation. Transformer construction has progressed somewhat since that time.

Dr. Steinmetz pointed out one of the weaknesses of the suspension type insulator (the multiple unit insulator), that is important to bear in mind. He calls attention to the fact that high-frequency disturbances are more apt to produce the concentration of potential than ordinary 60-cycle voltages. This is true, but yet we must remember that the capacity of each insulator in the series, and the capacity of each to ground, both vary with the frequency. The effect of raising the frequency is not to change the relation of the capacity of the insulators as units in the series to the capacity of each insulator to ground, but high frequency gives the capacity currents, as distinct from insulator leakage current, the power to determine the voltage.

Dr. Steinmetz has also made certain comments in his paper on an old subject that used to interest me very much and still does, and that is the matter of internal surges within transformer windings. The action of the surging on a transmission line is relatively easily understood. This is because the constants of the transmission line are uniformly distributed— the capacity per mile at one point is the same as the capacity per mile at another point. Similarly with the inductance. But within a transformer winding the capacity per foot of wire and the inductance per foot of wire vary in different parts of the transformer and change between the outer part of the coil and the inner part of the coil, between the line coil and the outside coil. There is also capacity between the high-tension coils on their surfaces opposite the low-tension coils, and opposite the core. The net result is that the condition of uniformly distributed inductance and capacity does not exist when the wire is wound into a coil on a transformer, and therefore none of the ordinary formulas for line conditions apply to the transformer; only empirical methods can be used.

Dr. Steinmetz is right in saying that a high-potential surge consisting of a single wave approaching from a line will enter to some distance into a transformer. I am inclined to think, however, that it is not a symmetrically preserved wave which passes along the winding from the terminal to the interior of the transformer, but rather that the rush of current in proceeding part way into the outer coil, which it first reaches, induces in the adjacent coils a similar rush of current, just as one transformer coil induces potential in another. Usually there are two or more high-tension transformer coils close together. You cannot produce a disturbance in one without producing by electromagnetic induction a disturbance in the other, and I am inclined to think that that is the real reason why the surge striking one coil will produce a surge which will be found in the next or subsequent coil.

I made some experiments some years ago to study this matter I worked on a transformer with ten high-tension coils very thin and very deep, arranged close together, where the conditions for mutual inductance were particularly favorable, and I traced the concentration of potential on the outer coil, which was struck by a static disturbance produced by an arc, and the effect was very marked on the first few turns, less in the next, and so on until it became normal voltage, taking the whole coil into consideration. The next coil had taps brought out permitting the measurement of the concentration of voltages there, and there were concentrated discharges on the turns of the inner coil, much less in magnitude, to correspond exactly with the concentration on the outer coil, and these induced currents from an electromagnetic field existing in the space about the coils—the transformer primary (first coil) induced current in the transformer secondary (second coil).

A. E. Kennelly: We are all indebted to Dr. Steinmetz for making so clear the peculiar differentiating conditions that occur in a string of suspension insulators, so that we may look upon these, in the future, from an electrical standpoint, as a sort of inverted Chinese pagoda. It is also very interesting to notice the effect of increasing voltages upon disturbances inside the transformer. We used to think that with one outer door we could limit all the high-frequency disturbances to the outside of a transformer, and keep every thing safe indoors. Now we find that we must not only barricade the stairs as well as the doors, to keep high-frequency disturbances from invading, but that we must also supply some kind of a fire escape.

In regard to that part of Dr. Steinmetz's paper which deals with the rise of voltage on long distance lines, we have at Harvard an artificial long distance transmission line which is 500 miles long, three-phase, or 1500 miles single-phase, probably the longest of its kind which has yet been built. It is very easy to make electrical measurements on such a line, because there are no difficulties with lightning, switching, synchronizing, or load variation. The advantage of such a line is that you can do on it in an hour what on an actual, regular transmission line it would take a week to accomplish, in the way of making observations and switching.

We have taken 650 miles of the artificial line, as being representative of the longest line likely to be produced in the near future, and have operated that at various frequencies, from 25 cycles per second up to over 400 cycles per second, and the differences produced are very marked. It is difficult to keep the frequency sufficiently pure. If there are harmonics in the impressed e.m.f., complications enter into the results, but if the frequency of the impressed e.m.f. can be kept very nearly pure, definite and easily verified observations are obtainable.

The results are being calculated and worked up for a paper that we hope to present at a later date.

In general, we find that at 60 cycles per second and 1000 km. or 621 miles of line, the rise of voltage at the distant end, with a sinusoidal e.m.f. impressed on the home end, is about 75 per cent, so that if you have 100,000 volts at the initial end you would have 175,000 on the distant end, without load. As the load is put on, there is a tendency to bring that excessive voltage down, but nevertheless, at what may be called rated load, there is still great difficulty in regulation, as Dr. Steinmetz's paper describes. If, however, we take 25 cycles per second, the rise of pressure is only 10 per cent instead of 75 per cent. The open end rise of voltage is therefore relatively negligible on 25 cycles per second, whereas it would be very serious, indeed, on 66 cycles per second with no magnetic reactance taps at intermediate stations.

When we come, however, to 400 cycles per second, we may get a rise of voltage of ten times the voltage applied. With a sevenfold frequency or a 420-cycle harmonic impressed on top of the 60-cycle generator, you can see that a 10 per cent ripple would be able to produce something like 100 per cent increase in voltage, compounded at right angles to, or by " crab addition " to, the fundamental; that is to say, 10 times 10 per cent would give 100 per cent, at right angles, or perpendicular to the regular pressure and that would mean 41 per cent increase by voltmeter. So there is good experimental reason to believe that a distinct rise in voltage at the distant end of the transmission line, on open circuit, may be due to the effect of ripples of a higher frequency.

The subject is very interesting and practical; but it is necessary to go slowly so as to check up each particular set of observations by calculation. One can secure more observations on the artificial line in an hour than can be worked out in a fortnight. Without hyperbolic functions, it would be hopeless.

A. S. McAllister: The inaccuracy of the term " reverse-current " relay is apparent when one considers that the relay is used in a circuit in which the current always reverses from 50 to 120 times per second. In no respect can the device be called a reverse-current relay. What reverses is the flow of energy, and the device is, therefore, a " reverse-power " relay. The incorrect term is in common use by the manufacturers, but it should not be permitted to appear in the TRANSACTIONS of the Institute.

Farley Osgood: First, I want to thank Dr. Kennelly for his new term " crab-addition." It is most original and unique.

I have very little to say in the nature of a direct discussion of either of these papers. I might give a word of caution, however, as an operating engineer, in the matter of the care of the relays. I do not think that Mr. Hewlett warned us quite enough as to this point. Unquestionably, the proper operation of this bit of apparatus depends very largely on its being carefully watched, carefully tested, and most important of all, carefully and often cleaned. The great trouble with relays is that they are such a comfort that when they work well we very largely neglect them, and leave them to go their way without any attention. The relay is a good friend, in good condition; but it is the worst friend we have, when it is in bad condition. A set of instructions properly drawn up, covering the periodic cleaning and testing of relays, should be enforced in any operating company; and the man in charge of the operation should insist, not only that the reports be sent to the chief at the specified time, but that the report should be fairly and honestly filled out by the men who do the work, stating that the work is done. Unless we help the designers of the relays by doing what they tell us we must do, there is no reason in the world for us to expect that the apparatus will serve our purpose, and I assure you that it will not.

C. O. Mailloux: The president has called attention to one of my early sins. I plead guilty to being one of the original inventors—I even think I was the *first* original inventor—of the automatic electromagnetic circuit breaker. I was its sponsor, and its wet nurse, and I assure you it was a very ticklish and troublesome task. However, it survived, and it quickly made a reputation, largely in the hands of other foster-parents, in other words, various manufacturing concerns promptly appropriated it, incidentally without giving any credit or any remuneration to the original inventor in spite of the broad patent which the Patent Office granted him for the invention twenty odd years ago. But I survived that, fortunately, and so did the circuit-breaker, and it has proved a very useful and practical device.

Now, the circuit-breaker as I first conceived it was a relay; it was nothing more than an adaptation of the relay. The first circuit breaker which I invented, and which I may say, incidentally, was first used on the first electric car which ran in New York City (a storage battery car), in 1887, was a " relay " circuit-breaker. My first attempt failed, because it followed too closely the original idea of the telegraph relay, but one idea led to another and eventually something else was added to the idea of the relay and in due course, a working device was produced. It may be said that necessity was the mother of invention in this case. In those pioneer days of electric traction, a motorman often used up his stock of extra fuses before the car returned to the starting point. My own personal experience in improvising fuses made up of bits of copper wire, at the most inconvenient times and places, was what made me think of using a *relay* to control a *switch.*

While I suppose that every one in the electrical business has had more or less experience with relays, none of us has had as much experience as those who have seen the relay at work and have dealt with it in telegraphy. Our president, Mr. Dunn, and our past-president, Dr. Kennelly, are both experts in telegraphic engineering, and they could tell us a great deal about the virtues and qualities of the relay in telegraphic work. If there is any device which is really accurate and satisfactory, and which has the smallest percentage of error of any piece of apparatus, it is probably the telegraph relay. When one considers the number of " clicks " it makes in a year, and the very small percentage of failures which it makes of its own accord (that is, eliminating the errors due to the operator), one must admit that the telegraph relay is a very perfect piece of apparatus.

Now, when one sees the service it has rendered in telegraphy, one may well ask why it cannot render equal service in other branches. We know that it has done it in railroad signaling, for instance, in automatic railroad signaling, a field in which it has rendered a great deal of very useful service. In the operation of automatic devices in connection with central station appliances the relay has given some good service, but very small, I think, in comparison with what it is destined to render.

My experience with the relay, as applied in certain stations, has been characterized by some of those experiences which were referred to by the first speaker. As one of the first inventors, if not the original inventor, of the switch-controlling relay, I have always had a fondness for using the relay; and I was one of the first men to attempt to use it in connection with high-tension work. This was some years ago; and I must say that it worked most often and best when it was cut out of the circuit, as another speaker said. It was usually found most reliable when there was an attendant to watch the apparatus and cut out the circuit if he heard the transformers roar too loud.

In spite of the fact that the relays would get out of order, and were, in some respects unreliable devices, which required a great deal of cleaning and attention and testing, I never entirely lost faith in them. I have always believed in them and I believe now that they have a great future. I have always believed that we can, by their means, do a great deal that we now depend on human intelligence to do. I believe the relay is destined to play a very important part and we are only just beginning to see its development.

The task of presenting the characteristics of relays could not have been entrusted to a better man than Mr. Hewlett, who is known to be one of the most experienced men in connection with the equipment of a power house in so far as the apparatus which is requisite for the regulation and control of the circuits is concerned. Those of us who have had occasion to deal with him and to find out what he knows or what he can suggest are well satisfied that the problem could not be placed in better hands, and I know that in his hands it will undergo a process of development that will eventually give us far better results than we obtain now, though even now we are beginning to obtain quite satisfactory results.

The paper of Dr. Steinmetz, especially, is one of those papers which may be said to fill one with a number of emotions and feelings because it brings to us in condensed form very many interesting facts and phenomena which most of us would never have surmised could possibly exist even a few years ago, and which, nevertheless, as we see, play a very important part in the possibilities of high-tension and long distance transmission. We find placed before us in intelligible form certain electrical phenomena with which we were all acquainted in their physical manifestations; for instance, the reflection of the wave, which is perfectly familiar to us as a phenomenon in optics, but which is not so easily grasped when we try to deal with it as an electrical phenomenon. The interesting facts to which Dr. Steinmetz calls attention, I think, are of the greatest significance and importance, and I am very glad indeed that there has been such an interesting discussion of them. I believe that the paper is one that will be very useful by the suggestions it contains and the realization which it brings to the mind of important facts that we had before ignored.

C. C. Badeau (by letter): The object of this discussion is to call attention to the very important point that, besides selecting the proper type of curve for the proper protection of a system, extreme accuracy of the relays producing this curve is absolutely necessary in order to get satisfactory operation, as I believe more trouble is caused by the inaccuracy of relays than by selecting a relay with the improper form of curve, and anything in the relay field which would tend to make relays more dependable and accurate should be welcomed.

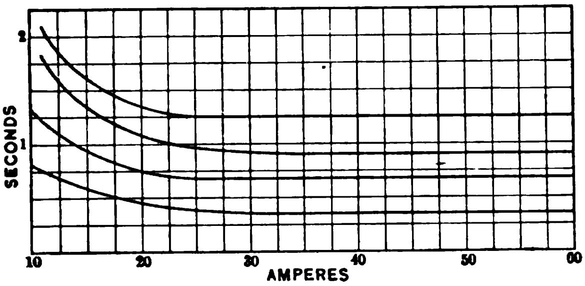

FIG. 1

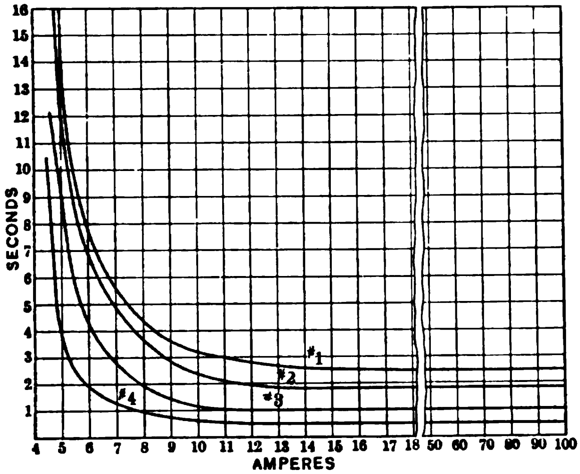

FIG. 1A

Some relay curves which differ slightly from those shown by Mr. Hewlett in his article are presented herewith. It will be noted that in Fig. 1 of this discussion the relay curves do not become parallel until 30 amperes is reached, that is, the action below 30 amperes is inverse and above 30 amperes is definite.

The curves produced by this relay also differ from those shown by Mr. Hewlett, as in all of the curves shown in Mr. Hewlett's article, except Fig. 2, the lines converge and tend to instantaneous operation, and a severe short circuit will destroy the selective action of relays set in this fashion. Mr. Hewlett has carried his curves out to 60 amperes, which is only twelve times full load current. Forty and fifty times full load current is not at all unusual on heavy short circuits, and with this amount of current, selective action, with relays which present such curves as shown in Mr. Hewlett's paper, is destroyed.

These are the times when selective action is required, and, therefore, the type of curve selected should be one in which, after the relay operates in a predetermined time, it cannot operate any more quickly, no matter how much current is passed through it. Relays having these characteristics—both as regards accuracy and curve—are now on the market and in use.

Charles W. Stone: There are two or three points involved in Dr. Steinmetz's paper to which I would draw attention. I think the main feature of this paper is the question of distributive voltages over the different disks in forming a string of insulators.

What Mr. Peek has said is a point that we may think a great deal more about a few years hence, and that is, that before we get to the economical limits, as far as electrical apparatus is concerned, we may reach the other limit; that is, the development of power load may be too slow to keep pace with the industrial development, and consequently, before we are able to reach out into a distance so great as to make it impossible to use the present type of construction, we will have a larger field for the market near at hand than we can supply.

The figures given by Dr. Kennelly are extremely interesting, in regard to experimental transmission lines, and they are exactly in accord with the figures we have arrived at in connection with a small transmission line of about 150 miles which has been built and installed in Union College in Schenectady.

The question of frequency has a very great effect upon the ultimate rise in voltage at the end of a transmission line, but I do not think it has been quite realized, in quantitative figures, what that comparison was.

I think that one thing that Mr. Thomas brought out in connection with the internal surges in the transformer perhaps may be misunderstood. I agree with what he said, so far as it went, but I think it applies principally to surges which have been started outside of the transformer. I think there are other surges that start inside the transformer, that are blanketed out by outside devices, and from those surges we have no means of protection at present.

E. M. Hewlett: Mr. McAllister brought up the point of the names of relays covering different functions, and I think it was an excellent point. We would like help on that point. It is hard to find descriptive names that seem to cover the different types and details of relays, and if any one can give us any suggestions for this purpose, I personally would be very glad to use them, and we will see what we can work out as the best names for different circuits. I think that is a matter the Institute might consider, and assign suitable terminology.

G. A. **Burnham** (communicated after adjournment): The subject of protective relays has been given serious consideration by engineers of late, and it is certainly a topic in which those concerned in the generation and distribution of electrical energy should be vitally interested.

As Mr. Hewlett has well pointed out in his paper, practically no type of relay will meet all conditions arising, even in the simple distribution, and the selection of relays for the protection of the complex interconnected network of our modern large capacity stations requires careful study.

In speaking of protective relays we naturally associate them with the opening of a circuit breaker in order to relieve a system of some abnormal condition. On the contrary, it is as much the duty of the relay to prevent the breakers from opening in order to maintain continuity of service.

The selection of a relay should not be determined entirely by the curve of its characteristics, although we must admit that the shape of the curve is of vital importance. I believe that accuracy and permanency should have at least as much bearing as the shape of the curve and should be the first consideration in the determination of protective relays, especially for selective operation of circuit breakers. It is not so important that relays should be extremely accurate on moderate overloads, but on short-circuit values of the current of, say, eight to ten times full load, the error should not exceed 0.1 sec.; in fact, recent developments have produced relays so designed that with a current in excess of twice full-load current the error in operation is negligible. This extreme accuracy is of importance in that it really reduces the total time of operation of the circuit breaker and relay, and it appears that with a relay of this type one-half second is really more time than is needed. For instance, if we assume 0.6 sec. for switch operation with two relays only, the total time, with one-half second setting between relays on the occurrence of a short circuit of, say, twelve to fifteen times full-load current, would be 1.6 seconds, which certainly is not desirable where a relatively large generator capacity is connected to the busbar. If the relays are set for one-quarter-second selection, the total time becomes 1.1 sec., or, in other words, the system is relieved of abnormal stresses approximately 40 per cent more quickly than with one-half-second settings. This is certainly of importance where synchronous apparatus is employed.

With extreme accuracy, a relay having a curve the first part of which is inverse up to a point, say, of four or five times full-load current and definite thereafter, irrespective of the value of the current, is desirable, as it tends towards continuity of service and still affords protection to the apparatus and cable system. In view of the tendency towards the use of power reactances to limit the possible short-circuit current to twelve or fourteen times normal, it appears that this type of curve should appeal to the operating engineer.

Another feature of extreme importance in time limit protective devices is the resetting feature of the relay. A relay should reset on at least 75 to 80 per cent of its minimum setting, and the circuit-closing contacts should instantly resume their original position.

Regarding Mr. Hewlett's statement in connection with the protection of separate feeders by the use of circuit breakers having a low rupturing capacity installed at the various distribution points or substations, and a master switch of relatively high capacity located at the main station, so arranged that a short circuit in excess of the rupturing capacity of the small switches would result in locking them and allowing the high-capacity breaker to open the circuit, it apparently is a step in the wrong direction, so far as continuity of service is concerned.

It appears to me that in large central stations the matter of protection is really decided by two factors—so-called short-circuit interruptions and continuity of service—and that the matter of moderate overloads is something which the switchboard attendant could control. This being the case, it appears that little advantage could be gained in having a circuit breaker at the substations or distribution points which was only sufficient to open moderate overloads, and this advantage would be more than overbalanced by having the large capacity breaker interrupt the service of all distributing points on that particular feeder. In other words, we would really have a feeder which has no protection from short circuits except the main switch at the main station, and in every event interrupting the entire service on the feeder. It does not appear to me that such an arrangement would meet with the approval of operating engineers.

E. A. Lof (communicated after adjournment): The protection of life and apparatus in connection with the maintenance of an uninterrupted service is a problem of utmost importance in any engineering undertaking. This is especially true in the present large electric power developments, which now mostly reach a capacity far beyond manual control. The expensive machinery and apparatus used in modern central stations and long distance high-tension transmissions makes it absolutely necessary to provide reliable automatic means for disconnecting generating units, transformers, transmission lines and distributing feeders at certain critical moments, both for the protection of the apparatus itself and for the maintenance of an uninterrupted and successful operation of the system.

The problem of protecting our power systems against shutdowns is therefore nowadays being given most careful attention, and all of our modern plants are equipped with automatic protective devices to meet almost all conditions of service. These conditions naturally vary greatly in different systems and a careful study must be made in each particular case to determine the most effective protection for the system in question. The following discussion of the relay applications to the systems most generally met with in our long distance transmissions may, therefore, be of benefit to some.

Fig. 2 represents the very simplest transmission system, consisting merely of one generator and step-up transformer, a single transmission line and step-down transformer. It is evident that the only protection which would be required for this system is an automatic generator switch. This should preferably be provided with the time limit relay, either of inverse or definite action, so as to prevent tripping of the switch on momentary short circuits, such as the swinging together of the line wires, etc.

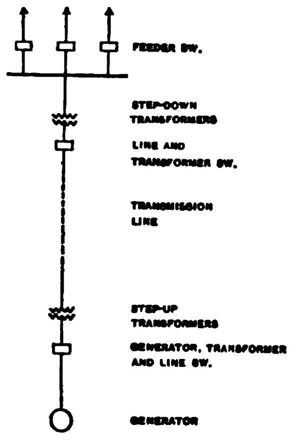

FIG. 2

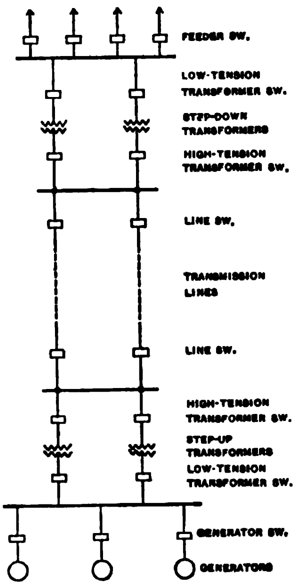

FIG. 3

The substation switch is not absolutely required, and if provided it need not be automatic. In certain cases, however, it may be advisable to make this switch automatic also. Its time limit relay should then be set lower than the relay in the main station, so that a short circuit, etc., in the substation would simply trip this switch and thus confine the trouble to the substation.

The switches for the distributing feeders should, of course, be provided with instantaneous relays, so as to immediately disconnect the feeder in which trouble occurs, without shutting down the rest of the system.

Fig. 3 represents a diagram of a system consisting of three generators, two step-up and step-down transformer banks and two parallel transmission lines. A low-tension bus is necessary on account of the different number of generators and transformers. A high-tension bus, preferably, should also be provided, so as to insure a satisfactory division of the load between the transformer banks. The generator switches in systems of this kind are often of the non-automatic type; the reason given by the advocates of this practise being, as stated in Mr. Hewlett's paper, the importance of keeping the generators in service in order to secure the most reliable operation, and the improbability of trouble between the generators and the busbars. The ability of alternating-current generators to stand a short circuit for some time will permit the operators to open the switches before any damage to the generators has been done. It seems, however, that it would be much safer to make these switches automatic, in which case the relays should be of definite time limit type, set very high. Reverse-current relays can also be installed. On a short circuit in one of the generators the current in this circuit will naturally reverse, causing the relay instantaneously to open the switch, thus entirely disconnecting the damaged generator from the system and preventing the other generators from feeding into the short circuit. The objection to this type of relay is, however, that on short circuits it will practically act as an instantaneous overload relay, and may cause opening of all the generator switches, and thus a shutdown of the entire system.

For protecting the two transformer banks, oil switches should be installed on either side. In case of trouble in one bank selective action should be provided, so that the injured bank can be disconnected immediately without interrupting the other. This can be accomplished by means of instantaneous differential relays. This relay consists of two coils connected to current transformers in either side of the transformer bank. Ordinarily the effect of one coil neutralizes that of the other, but on a reversal of current through one of the coils, each coil assists the other in operating the relay plunger, thus instantaneously opening both the high- and low-tension transformer switches.

This method, however, gives no protection against overload. If this is required, inverse time limit relays are installed for the low-tension transformer switches and instantaneous differential balance relays for the high-tension switches. On a short circuit in one of the banks, the relay for its high-tension switch will then act on the reversal of the current and instantly open the switch, at the same time locking the relay of the other high-tension transformer switch, thus preventing it from opening on overload. The low-tension switch of the injured bank thereafter opens, thus selectively disconnecting the faulty bank. It is evident that inverse time limit relays for all the switches would not insure a selective operation, as the current through all the relays would have approximately the same value, thus causing all the switches to trip simultaneously.

The protection of the two transmission lines offers the same problem as just outlined for the two transformer banks, *i.e.*, the main station switches should be equipped with inverse time limit relays and the substation switches with instantaneous differential balance relays.

The step-down transformers in the substation should also be protected similarly to the transformers in the main station, and the feeder switches should be equipped with instantaneous overload relays, so as to cause an immediate disconnection of the feeder in which trouble occurs.

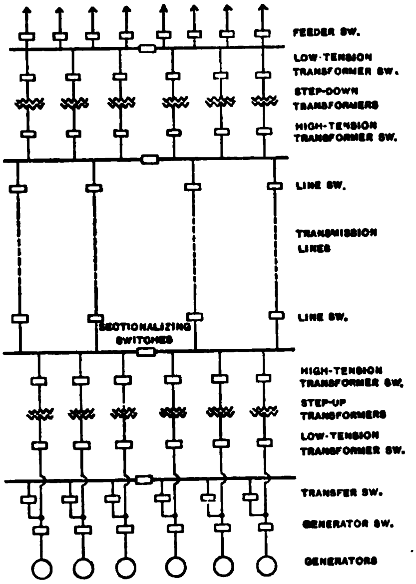

FIG. 4

Fig. 4 is a diagram of a system of considerable magnitude. One transformer bank is provided for each generator and no low-tension bus is required; a transfer bus, however, being installed. What has been previously said about the protection of the generators applies in this case. Either non-automatic or automatic switches with definite time limit or reverse-current relays can be provided, while the transfer switches generally are made non-automatic.

Both the low-tension and high-tension transformer switches should be provided with inverse time limit relays, or both switches can be operated from an inverse time limit relay installed on the side of the transformer which is opposite to the source of power, *i.e.*, the high-tension side of the main station. This relay is then arranged to trip both switches and give selective action, as it is obvious that if a short circuit should occur in one bank the current through this relay would be practically the sum of the currents through the other relays, thus causing the relay in the faulty circuit to act more quickly. This applies also to the protection of the substation transformers.

Inverse time limit relays will evidently also give selective action for the transmission lines, when more than two are installed.

When the total generator capacity exceeds the rated rupturing capacity of the switches, it has been common practise to provide one or more sectionalizing switches in the busbars. They are usually made automatic and provided with instantaneous overload relays, so as to confine any trouble to one section, and prevent the switches from rupturing more than their rated capacity.

A paper presented at the Baltimore Section Meeting of the American Institute of Electrical Engineers, Baltimore, Md., March 27, 1912.

ECONOMIES IN RAILWAY OPERATION

BY F. E. WYNNE

Never before in the history of modern industrialism has there been such a stupendous effort made by every one for high efficiency as at the present time. It is the keynote of every convention; the proceedings of the Institute and other engineering societies are full of it; magazines and daily papers are devoting a great deal of space to the subject.

Under such conditions it is natural that the pendulum in railway operation, which has until recently been swinging far upon the side of safety and reliability at any cost, started to swing towards the side of reduction in cost, at the price, as some engineers think, of both safety and reliability. When this happens, an extreme is likely to be reached that may show a reduction in cost of some items that have been in the limelight, but will show an increase in other items affected thereby that will far outweigh the reduction. The way to avoid such an undesirable condition of affairs is to analyze carefully every point and study it from all sides before making a change from practise that is giving good results. In other words, the old maxim, " be sure you are right, then go ahead," applies here with special force.

Probably nowhere has this search for efficiency been more active than in the electric railway field. In the first place every part of the equipment has been studied with the greatest care to increase its life and reliability and decrease the cost of maintenance. This has resulted in the present magnificent equipments that are found on all up-to-date roads. Car bodies, trucks, wheels, control and motors have all been improved to an extent undreamed-of a few years ago. Not only has there been a great increase in reliability—which is always one of the greatest assets a road can have—but the cost of inspection and maintenance has been reduced to a degree that makes it cheaper to scrap old equipments than to operate them.

Since the life of wearing parts has been increased to such an extent that but little return may be expected from further endeavors along that line, the busy minds of engineers all over the country have been turned towards other means of reducing cost of operation and have naturally rested on the cost of power. This is usually one of the larger items in the cost of operation and offers a fruitful field for investigation. A great many engineers have figured out the amount it costs to carry around the dead weight of a car and have given figures varying from 3 to 10 cents per pound per year. These figures must of course depend on the mileage, the cost of power per kw-hr. at the car, and the kind of service. For instance, the mileage of cars may vary from 15,000 to 90,000 miles per annum. Power may cost in one place 0.4 cent per kw-hr. at the switchboard, and in another place may run twice that amount. Then the cost of getting a kilowatt-hour from the power house to the car varies widely. Finally, the conditions of service may vary so much as to take anywhere from 40 to 150 watt-hours per ton-mile at the car. A road which averages 50,000 miles per car per annum, consuming 100 watt-hours per ton-mile at the car, and whose power costs 1.5 cents per kw-hr. at the car, will pay 3¾ cents per pound per annum for power.

$$\frac{50{,}000 \times 0.100 \times 1.5}{2000} = 3\tfrac{3}{4}$$

But whatever the actual cost may be, it has put the matter before the operating people in such an attractive way that many of them have been bending every energy to reducing weight, thinking that every pound reduced, no matter how reduced, will result in an immediate saving of 5 cents per pound per annum. Some even go so far as to say that every pound removed from the dead weight of a car is worth 75 cents to them—off the car. This is the kind of talk that must be accepted with a good deal of reservation. It is no doubt true that if the cost of operation per ton-mile remains the same with the lighter weight cars and equipments, the saving will be made. The danger is that in reducing the weight, conditions may be altered so much as to make the cost of operation more than before. The cost of inspection and maintenance may be increased on account of the necessity for more frequent renewals of wearing parts. It is intended to discuss in this paper some of the proposed means for saving power on electric railroads and to clear up, if possible, some of the misunderstandings that exist at the present time.

I. Reduction of Weight

In the development of the electric railways, the evolution of cars and equipments from the old horse cars to the modern double truck city cars and the high-speed interurban cars has been attended by much grief and loss. The development was so rapid that the only method possible to pursue was to build the car and equip it, using the best judgment available in proportioning the parts. Where parts broke in service, they were usually strengthened by increasing weight and section, regardless of the actual cause of the break, which might have been in something entirely different. This of course resulted in designs which were unnecessarily heavy. It is the part of good designers and conservative engineers to re-design them, distributing material where necessary for strength and cutting out as much unnecessary material as possible. It is astonishing what results have already been attained in this line, and the end is not yet. The use of high-grade materials and pressed steel shapes with new types especially fitted for them will still further reduce weights of car bodies and trucks, and now the question has been put squarely up to the electrical manufacturers to reduce the weight of the motors and control apparatus.

Motors. The weight of motors may be reduced as follows:

1. By cutting out all useless weight; in other words, by very careful designing.
2. By the use of high grades of metal to give the necessary mechanical strength with smaller sections.
3. By the use of higher grades of insulation which will allow operation at higher temperatures and thus permit the use of smaller motors.
4. By the use of forced ventilation, thus enabling the motor to carry larger continuous loads with safe rise in temperature.
5. By increasing the armature speeds, which thus gives a greater output to a given size of motor.

1. *Improved Design.* The first method of cutting the weight, that is, by eliminating all useless weight, is a quite obvious one, and has been followed to a greater or less extent for years. It

is now being worked to the limit, and it is safe to say that all motors which are designed hereafter will have a minimum of useless weight in them.

2. *High-Grade Metals.* Higher grades of material have also been used more or less, and there are now very few motors that have cast iron in them where weight would be saved by the use of malleable iron or of steel. Heat-treated steel is also used in some cases for shafts, and will probably be used increasingly hereafter. At present, however, its use on standard apparatus is attended with danger and expense, since the methods of heat-treating steel are not generally well-known, and, where special materials are used, it always results in more or less dissatisfaction in making repairs. In any case, the reduction of weight in shafts that is possible by this method is very limited, since the reduction in diameter reduces the stiffness in the shaft very rapidly, and even if the shaft is of the high-grade material, it is not safe to permit the deflection.

Great improvements have been made in steel castings in late years. This permits the use of thinner sections than it has been possible to cast heretofore. This will reduce the useless material.

3. *High-Grade Insulation.* A certain amount of increase in capacity from a given size of motor may be obtained by the use of heat-resisting insulation, and it has been common practise for years to make use of such insulation in the larger sizes of motors and in field coils for smaller motors, it being common practise to use mica insulation for armatures and asbestos-insulated copper strap for field coils. It is very difficult to increase the output of machines so insulated above that which has been obtained for years. Small wire-wound armatures have been wound in many cases with the wire insulated by preparations of asbestos which have increased the safe temperature limit very materially in such machines. Such insulation, however, must be handled with much greater care than ordinary coils insulated with cotton or similar fabrics, as the asbestos is very weak mechanically, and armatures are more liable to short-circuit. The net gain in capacity by using high-grade insulation is somewhat reduced because better insulating materials are poorer heat conductors and a given load produces higher motor temperature than with poorer insulation. The limit to the temperature in motors at present is the melting point of tin solder, and we believe that very little increase in temperature above the present limits will be possible until a soldering material with higher melting point is produced.

Tin melts at a temperature of about 225 deg. cent. This seems like a good margin to give a motor which is supposed to operate around 75 to 100 deg. cent.; as a matter of fact, the sudden heavy loads on motors which do not last long enough to heat up the entire armatures will last long enough to melt the solder out or at least soften it to a point where it is thrown out by centrifugal action. This probably will be much more frequent when the motors are normally operated at higher temperatures than at present. Therefore, we feel that this offers no great increase in capacity. At least, any increase in capacity thus produced will be obtained simultaneously with the lower efficiency of motor, since in most cases a small motor operated at heavy overloads and high temperatures will have a lower efficiency than the size larger motor operated in the same service. Thus part of the saving which is effected by the use of a little lighter weight motor is lost in the decreased efficiency of the motor.

4. *Forced Ventilation.* The fourth method of increasing the output, namely by forced ventilation, has been in use for some years, and is quite effective. It is surprising what an effect a small amount of air circulating through the motor will have on the temperature, and capacity. It has the effect of increasing the continuous capacity of motors, which ordinarily is not more than 45 to 50 per cent of the one-hour current rating, to 65 to 80 per cent of the hour rating. In locomotives, air is forced through the motors by motor-driven blowers in the cab. These blowers take their air chiefly from the outside of the cab through louvres in the side wall of the cab. The air is taken at a sufficient distance above the road-bed so that very little dust is blown into the motors, consequently, they remain quite clean inside.

The single-phase locomotives for the New York, New Haven and Hartford Railway Company were probably the first machines that employed the use of forced ventilation on a large scale. This system is used on all of the single-phase locomotives and some of the motor cars now in use, not only on the New Haven system, but on the Spokane and Inland Empire Railway, St. Clair Tunnel, Rock Island and Southern Railroad, and others. The later locomotives on the New York, New Haven and Hartford Railroad, the first of which has been in operation for two years, are also supplied with fans on the rear end of the armature, which are so arranged as to draw air through longitudinal holes in the armature core, thus greatly increasing the effectiveness of the air which is forced in from the outside. In cases where these motors are extended through the floor of the cab into the interior it is usual to circulate the air through the motor by means of the fan on the motor itself, and the external blower is unnecessary. Where the motor is below the floor and exposed to all the dust and dirt, it is undesirable to permit the air to be drawn into the motor, as it will draw with it too much dirt and will invariably deposit it on the inside of the motor. A great deal may be accomplished by the use of fans on the armature, with openings through the armature. This establishes a circulation of air inside of the motor, thus bringing the air in contact with the outside of the motor frame, which can radiate it. The radiating surface of the motor may be increased by the use of ribs cast on the outside of the frame as is done in air compressors and such things as automobile radiators. The greater the external surface of the motor, the greater the radiating surface will be, and consequently the lower the temperature of the motor.

5. *High Armature Speed.* Increasing the armature speed is permissible where it can be done without sacrificing economy of operation. Cars which are operated at high speeds may have high-speed motors on them, the limit to the speed being simply mechanical considerations. It is governed entirely by the maximum speed at which the cars are to be operated. This method has also been in use for years, as it has been common practise to have two or more motors of different capacity but approximately the same weight. A certain frame is adapted to give a certain torque at the armature shaft. This will usually be somewhat greater with a low-speed winding than with a high-speed winding, but roughly speaking, it is a constant, and the horse power rating of the motor will consequently be increased as the speed is increased. Thus a motor which at ordinary speeds would develop 30 h.p. may, by increasing the speed about 35 per cent, be able to develop 40 h.p. Such high-speed motors are very satisfactory for high-speed service. Where low schedules are required, high armature speed has the same effect on the efficiency of operation as the use of a small gear reduction on a low-speed motor. It is a fact which has been well known for years, and is now almost universally accepted, that an equipment with a high-speed gear ratio on city cars will use a great deal more power than the same equipment would take if supplied with the maximum gear reduction. The recognition of this fact has resulted in a wholesale change in gear ratios on the cars in many of our large cities, notably Brooklyn, Chicago,

Baltimore and Pittsburgh. It will in most cases be found that for ordinary city service a motor operating at a full load armature speed between 450 and 550 rev. per min., when supplied with its maximum gear reduction, will give the greatest economy in operation. Motors operating at 600 to 700 rev. per min., if supplied with maximum gear reduction, will require more power on account of greater rheostatic losses in starting. Consequently, it is very essential that care be taken in selecting motors, not simply to pick the motor having the lightest weight, but to select one which has the correct speed and torque characteristics. It will be found that far more can be saved by gearing the motor for the most economical speed then can possibly be saved by any reduction in the weight. It is not at all uncommon to save 15 per cent or 20 per cent in power by a change in gear ratio, while the weight of the motors alone cannot be changed by increasing the speed so as to affect the total car weight more than five per cent. Further, any increase in armature speed above the economical speed will not reduce the weight of motor required for a given service, for the root-mean-square current of the high-speed motor will be greater than that of the low-speed motor, in proportion to the increase of speed, which is proportional to the increase in capacity. Therefore, a given service will produce equal heating in motors of the same weight but different speeds, with the same gear ratio.

Control. The weight of control apparatus may be reduced as follows:

1. By improved design of parts.
2. By more efficient arrangement of switches.
3. By more efficient use of resistance.
4. Better location of apparatus on the car.

1. *Improved Design.* As in motors, better design will eliminate all useless weight from control apparatus. Here, also, high-grade material may be employed to advantage, and it is probable that the greatest reduction in weight will be effected by the use of structural and sheet steels in places where cast iron is used at present.

2. *Improved Arrangement.* Where a number of similar operations are to be performed by a number of similar units of apparatus there is the possibility of accomplishing the same result with widely different numbers of units. Reducing the number of units required to a minimum is a matter of development, and frequently there is a chance that some new combinations of units

may be discovered which will employ fewer units than required by present standards and so reduce the weight of the control equipment. An example of this occurred in connection with the control for high-voltage direct-current motors, when a new scheme of connections was devised so that only 13 unit switches were needed to perform the same functions for which 18 switches had previously been used. Incidentally, with the smaller number of switches more breaks in series were obtained, resulting in a better as well as lighter control.

3. *Better Use of Resistance.* In modern equipments, the weight of the resistance may be roughly from 10 per cent to 20 per cent of the total weight of all the control apparatus. By using the same sections of resistance in different combinations for different controller notches, not only may the weight of resistance be reduced, but the number of switches employed may be decreased and the main wiring lessened.

4. *Better Location of Apparatus.* The amount of wiring may be reduced to a minimum by carefully arranging the apparatus under a car. It is often also possible to cut down the weight of hangers required from that which at first seems necessary. More could be accomplished in this respect by closer cooperation between the car builders and electrical manufacturers.

Two-Motor Equipments. In many of the large electric railways and steam railroad electrifications, the advantages of two-motor equipments in place of four-motor equipments have long been appreciated. Where only half of the wheels are available for adhesion, of course the conditions of grade and climate must be such that from 60 per cent to 75 per cent of the total car weight will permit developing sufficient traction for all the requirements of the service. Where the full weight of the car is required for adhesion, the two axles of a truck may be connected by side rods. Experiments have been made in this line with more or less success, and complete success depends only on the design of truck, including side-rods, and method of hanging and applying brakes.

With two motors, the total equipment weight per horse power is from seven per cent to 30 per cent less than with quadruple equipments, because the two motors weigh less than the four, the control apparatus is lighter and less wiring is required. A further gain may be made in the trucks, since the weight of two trucks *may* be less and *need* be no greater for two large motors than for four small ones.

In addition to having a higher weight efficiency, two-motor equipments have higher electrical efficiency and reduced first cost and cost of maintenance.

II. PROPER GEARING AND ARMATURE SPEED

"The selection of improper gear ratios for railway motor equipments has alone caused a loss of hundreds of thousands of dollars to the operating and manufacturing companies in this country. Motors have been overloaded and burned out by the thousands. Fifty-horse power motors have been used where forty-horse power motors would have done equally well if properly geared. Power houses and substations have been overloaded, have had their load factor greatly decreased and the line loss has been greatly increased, simply because the motors on the cars have been geared for too high speeds. Few people who have not made a special study of the subject realize its importance, and at the present time, in spite of the campaign which has been waged against it by the manufacturing companies and a few enlightened engineers, there are still a good many motors in service which are so geared as to result in a continual loss to the operating company. The large companies have been realizing more and more in recent years the disadvantages of high-speed gearing and some of them are now making wholesale changes in their gearing, reducing the maximum speeds and making savings of five to twelve per cent in power consumption, besides greatly reducing the temperature of the motors."[1]

"Probably the most common error in gearing is to gear for high speed where the service is such that the stops are frequent and there is no opportunity to run at high speed. The typical cycle for such runs is rapid acceleration, short coast and rapid braking. Consequently the acceleration and the run, to be accomplished most efficiently, would be made with a low-speed gear. That which is so self-evident in this case holds good in lesser degree with longer runs. Therefore, having selected a motor with sufficient capacity for a given service, the best gear ratio to use is the lowest speed gear which will give the required schedule speed with a reasonable margin for making up lost time."[2]

Probably five to ten per cent of all the power used for propelling electric cars and trains could be saved by correct gearing.

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[1] N. W. Storer in *Electric Journal*, Vol. V, p. 510.

[2] F. E. Wynne in *Electric Journal*, Vol. III, p. 379.

The maximum gear reduction varies from 3.5:1 to 5:1, depending upon the power of the motor. The armature speed at the 500-volt rating of the motor varies from 500 to 650 rev. per min. Therefore, with maximum reduction and minimum wheel diameter, the car speed at full load of the motors varies between about 10 and 18 miles per hour. Even motors of the same power are built for such speeds that with the same gearing, the car speeds differ by as much as 25 per cent. The opportunity for incorrect motor application, particularly where stops are frequent, is therefore apparent.

City Service. By city service we mean the service in the larger cities where stops average seven or more per mile and are fairly evenly distributed. In such service there is very little or no running at full speed. The essentials for maintaining the schedule are rapid acceleration and braking. In most cases there is no difficulty in keeping cars on time with the motors geared with the maximum reduction. Under such conditions a motor of low rev. per min. with the same gear reduction, will do either one or two things; it will give the same rate of acceleration with less current or with the same current it will give a higher rate of acceleration than the motor of higher rev. per min. Both of these features tend to reduce the power consumed.

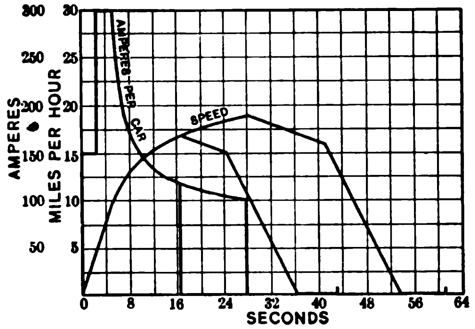

FIG. 1

As an illustration compare the shorter runs in Figs. 1 and 2. In each case train, grade and curve resistance has been taken at 22 lb. (9.98 kg.) per ton. The low-speed motor of Fig. 2 takes the same accelerating current as the high-speed motor of Fig. 1. Because of the quicker start with the low-speed motor, the heavy current does not last so long, the same amount of coasting is obtained, and the brakes are applied at a lower speed. The gain in power consumption in favor of the low-speed motor is 10.9 per cent. Part of this saving is the result of lower rheostatic losses and the balance is due to the smaller amount of stored energy wasted in the braking process. It should be noted that the gain of 10.9 per cent is in total power consumed and is in spite of the extra weight of car with the low-speed motor. It is further worthy of note that the heating of the high-speed motor is the greater.

These curves will also serve to illustrate the effect of gear ratio. The high-speed motor corresponds to the low-speed motor with a 4.43:1 gear reduction. However, in this instance the car weights should be the same so that the difference in favor of the low-speed gearing is even a little greater than the 13.8 per cent saving indicated by the watt-hour per ton-mile values of the figures.

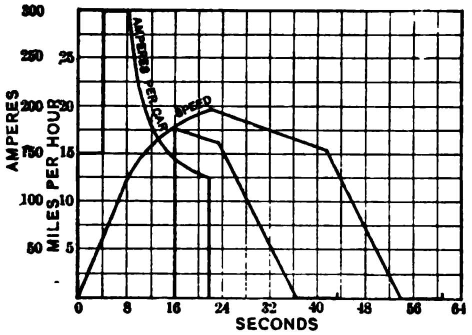

FIG. 2

The motor speeds used are within the limits of commercial apparatus and the gearing is within the limits found on the same motors in the same service, so that actual service conditions are represented.

The argument most frequently heard against the adoption of low armature speed and high gear ratios for city service is that the car speed will be so low that the running time will be greater. Let us examine this contention and see of how much value it really is. Figs. 1 and 2 show that the two motors make the schedule equally well. The higher acceleration is obtained with the low-speed motor without subjecting the equipment to any heavier current. The amount of coasting is practically the same, so that if the runs were made without any coast, the times would be the same. The high-speed motor is already slightly overworked, so there is no hope of making a faster schedule by forcing its rate of acceleration up to the value which is safe with the low-speed motor. Neither can the high-speed motor take advantage of more rapid braking to increase the schedule speed. However, since the low-speed motor is not yet worked up to its full capacity, it can use faster braking to a certain extent without being overloaded.

The figures given above show the saving in power at the car. This is further augmented by the accompanying reduction in losses throughout the system from the cars to the coal pile on account of the reduction in the duration of peaks and the improved load factor with low-speed motors. Therefore the figures given are conservative. The assumption of equal gear reduction is fair because the maximum gearing is fixed by the power of the motors and the clearance between gear case and track.

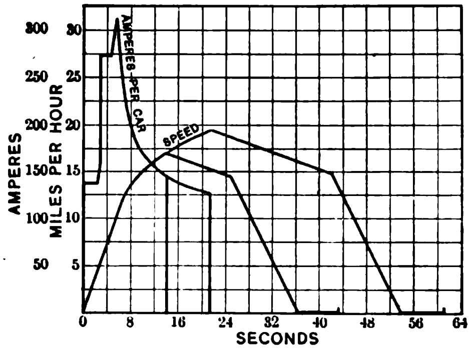

FIG. 3

Now consider whether the saving due to less weight will make up for the loss in power consumption. If the car under consideration makes 30,000 miles annually, the car with light high-speed motors at 4.21 kw-hr. per car-mile will consume 126,300 kw-hr. annually, while the car with low-speed motors will consume 112,500 kw-hr. The annual saving is 13,800 kw-hr. At one cent per kw-hr. this amounts to $138. At five cents per pound per year, the high-speed motor car would save $100 annually. The net saving is $38 annually in favor of the low-speed motor. The actual difference is more than this because part of the saving of five cents per pound annually is based on reduced power consumption with the high-speed motor. We have shown that this basis is incorrect.

If the heavier car consumed the same energy per ton-mile (145 watt-hours) as the lighter car, the latter would save in energy 4350 kw-hr. annually. Hence $43.50 of the $100 annual saving credited to the light motor above is not really obtained, and the actual net saving for the low-speed motor is $81.50 per year.

Many railway systems are facing the problem of operating more cars, while their generating and distributing systems are already loaded to their full capacity. The reduction in power consumption with low-speed motors would mean that more cars could be operated without increasing the generating and distributing capacity. So the questions of motor speed and gearing are exceedingly important when considering the installation of a new system or a new line. It is unfortunate that this has not been better appreciated in the past.

Combined City and Suburban Service. Here are considered those lines giving a mixed service consisting in part of city service as defined above and in part of a service averaging four or five stops per mile, with more or less well-defined limits.

In this class of service the same general principles hold as for city service. The possibility of using high speed is only slightly greater than in city service, as the stops are still comparatively frequent.

For example, assume that the operation of a certain line comprises six miles of city running with nine stops per mile and six miles of suburban running with five stops per mile. The minimum running time without any coast is 68.8 minutes for the low-speed motor and 68 minutes for the high-speed motor, a difference of 0.8 minute or 1.16 per cent. On the basis of a schedule time of 81 minutes for the run one way, and operation of the two motors as shown in Figs. 1 and 2, the power consumption with the high-speed motor is 42.54 kw-hr. per trip and with the low-speed motor is 39.9 kw-hr. per trip, the latter saving 6.2 per cent of the energy required by the former.

In this class of service the annual car-mileage is generally higher than in city service only, on account of the longer trips, somewhat higher average speeds, and smaller difference between the average and maximum number of cars required at different times of the day and year. Assuming 40,000 miles per car yearly and power at one cent per kw-hr., the saving by using the low-speed motor instead of the high-speed motor amounts to $46 annually.

Interurban Service. Practically all interurban railways enter one or more large towns or cities over tracks laid in the streets for several miles. This condition generally requires low-speed running whether the stops are few or frequent, and therefore this part of the service is most economically maintained by the lowest-speed gearing suitable for the other service. Many of these railways give both local and limited service. It is of course desirable to use the same motor and same gear ratio for both classes of service. With the same gearing, the local service, because of the more frequent stops, will work the motors more nearly up to their full capacity than will the limited service. The limited service is most often considerably less than half of the total. In order to minimize the size of equipment and get the maximum economy of power, the gear ratio should be selected on the basis of the local service, and the limited schedule adjusted to suit the equipment and gearing best adapted to the local service. If a high-speed limited schedule is taken as the basis of choosing the gear ratio, one of two evils frequently results: (1) a small equipment geared for abnormally high speed and just able to maintain the limited schedule nicely, is selected, with the inevitable result of overheating the motors in local service, roasting out the windings, loosening connections and consuming an unwarranted amount of power; or (2) a large equipment geared to maintain the limited schedule and yet of sufficient capacity to perform the local service without overheating, is chosen, with the result that the power consumed in local service is excessive and equipments are heavier than need be for the major portion of the service. With the large motor geared for a high limited schedule, the heating in local service is as great as with the smaller motor properly geared for the local service.

Large high-speed equipments collect their toll all along the line through extra weight, first cost, cost of maintenance, cost of power, greater feeder capacity, larger substations and larger power houses. Is it worth the price? We believe it is not. In certain cases of keen competition, it may rise to the dignity of a *necessary* evil, but too often high speed is assumed as the essential element in building and maintaining traffic, when in reality the frequent service and ability to receive and deliver passengers at several central points in the terminals and towns served, assures all the profitable traffic.

In the last analysis we believe that the extra cost of excessively high speed limited service is rarely equalled by the additional revenue obtained on account of the excess in speed over what could be secured with equipments geared for moderate speed.

Table II shows that the power consumption per car-mile for local service is 2.4 kw-hr. with 75-h.p. motors and 2.7 kw-hr. with 100-h.p. motors, and for limited service is 2.03 kw-hr. and 2.39 kw-hr. with the 75-h.p. and 100-h.p. motors respectively.

III. Correct Operation

We have shown that very great economies may be obtained by selecting motors of the proper armature speed and correct gearing. In addition to these, a great saving in power consumption may be secured by correct operation of the cars in service. By correct operation is meant the use of proper accelerating and braking rates so as to obtain the greatest amount of coasting consistent with the particular equipment used in any given service.

Acceleration. It is frequently found that where a road is operating under a fairly easy schedule, the motormen will accelerate rather slowly and perhaps operate with the motors connected in series for a considerable part of the time. The limits to the rate of acceleration are the strains on the car and equipment and the comfort of the passengers, so that all of these features should be considered in determining the maximum rate of acceleration which is permissible in any given case. So far as comfort is concerned, rates of acceleration up to 2 mi. per hr. per sec. are in use without objection on the part of the passengers.

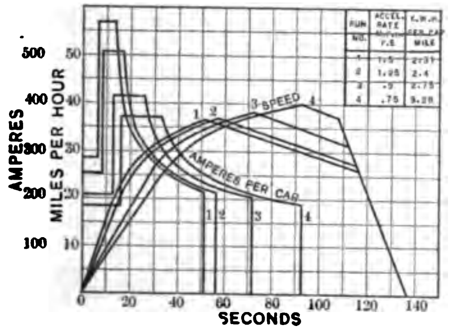

Fig. 4

Fig. 4 shows a run of one mile at a schedule speed of 24 mi. per hr. with various rates of acceleration. The car weight is 38 tons and the equipment comprises four motors, each rating 75 h.p. at 500 volts. The braking rate is constant at 1.25 mi. per hr. per sec. A consideration of this figure shows that by varying the acceleration from 0.75 mi. per hr. per sec. to 1.5 mi. per hr. per sec., the power consumption may be reduced 29.6 per cent. It should be noted in this connection, however, that the maximum current requirements vary from 370 amperes per car with the lowest rate of acceleration to 570 amperes per car with the highest rate of acceleration. Hence substation and line capacity must be considered in many instances.

Coasting. The amount of coasting obtained is a fairly good measure of the difference in power consumption for a given run made under different conditions; because when the amount of coasting is great, it usually means that the acceleration is rapid and that the braking rate is also high. The actual economy obtained by increasing the amount of coasting in any given service is not effected during the coasting period itself, but is the result of (1) more rapid acceleration with power taken from the line a decreased proportion of the time, and (2) of a higher braking rate with decreased waste of energy in heating the brake shoes and wheels.

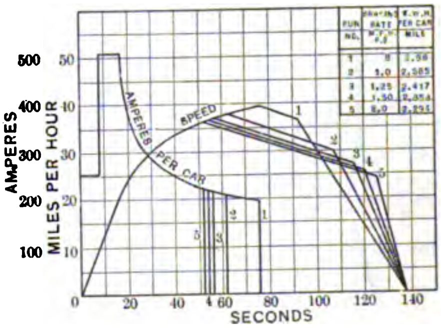

Fig. 5

Braking. Other things remaining the same, an increase in the braking rate produces a decrease in power consumption, because the brakes will be applied at a lower speed and consequently there will be less of the stored energy of the car consumed during the braking period. This saving is indicated directly by the decreased time during which it is required to supply power to the car in order to maintain a given schedule.

Fig. 5 shows the same run as in Fig. 4 except that a constant accelerating rate is maintained and the braking rate is varied. By varying the braking rate from 0.8 mi. per hr. per sec. to 2.0

mi. per hr. per sec., the power consumption is reduced 23.1 per cent.

Fig. 9 is a general curve showing the rheostatic losses in an equipment, plotted against the speed at which the rheostats are all cut out of the circuit, the stored energy in a car at any speed, and the power input to the car in bringing it from rest up to any given speed. The energy to propel a car is utilized in heating the electrical equipment, overcoming rheostatic losses in starting, in heating brake shoes and wheels and in overcoming the friction and windage due to operating the car in service. The latter item is the useful work and is practically constant for a given service irrespective of the method of operation.

By using a motor so designed and geared that the rheostats will all be cut out of circuit at a low speed, the rheostatic losses will be below those obtained when the rheostats are cut out of circuit at a higher speed. With a given equipment, increasing the rate of acceleration produces this result. Higher rates of acceleration permit the car to coast to a lower speed before the brakes are applied and therefore less energy is wasted in heating the brake shoes and wheels. High rates of braking accomplish the same result.

The curve in Fig. 9 marked " rheostatic losses " shows what may be accomplished by cutting out the rheostats more quickly. The curves marked " stored energy, no rotational" gives a measure of the amount of energy wasted in braking from any given speed and shows what may be accomplished by applying the brakes at a lower car speed. This curve is used in preference to the one including the energy of rotation in armatures, gears, wheels and axles, since this rotational energy will be about balanced by the train resistance while braking. The curves for field control will be considered later.

The coasting clock has been used with considerable success in decreasing the power consumption by inducing the motormen to accelerate and brake at higher rates. There are two points to guard against in its use, however; one is that the rates of acceleration and braking be not forced up to such a point that both excessive mechanical and electrical strains may be imposed upon the equipments with a resultant increase in the maintenance account; the other, that when the transportation department find that a certain schedule can easily be maintained with 30 or 40 per cent of the time spent in coasting, they must not yield to the temptation to decrease the running time, and run the risk of over-heating the equipments.

IV. FIELD CONTROL

The control of the speed of railway motors by changing the effective turns on the field, is as old as railway motors. Practically all of the early double-reduction motors were controlled in that way. Some few single-reduction motors were also controlled in that way and the old "loop" system was quite familiar fifteen years ago. It was a failure at that time chiefly because of difficulties with commutation due to poor motor design. Its advantages have remained fresh in the minds of some engineers, however, and when the locomotives for the New York, New Haven and Hartford Railroad were designed in 1905, they were arranged for speed control on direct current by shunting the field. Forty-one locomotives have been in operation with this system of control on this road for the last five years and it has proved entirely satisfactory.

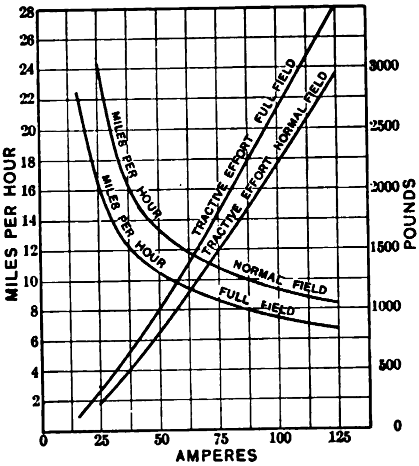

FIG. 6—FIELD CONTROL—40-H.P. MOTOR—5.12 GEAR RATIO—33-IN. WHEELS—500 VOLTS

When the giant Pennsylvania locomotives were designed, the requirements for large tractive effort in starting and high maximum speed were so severe that it was necessary to use field control of the motors. The application was slightly different from that of the New Haven locomotives, however; instead of shunting the field, half of it is cut out on the final notches in series and parallel. This is to avoid having a non-inductive shunt around the field which with a solid frame machine, might be productive of flashing. This is the scheme which has since been tried with great success on motors for city and interurban cars.

The question that naturally arises is, what are the advantages of this system? The answer is brief, to save power. How is this accomplished? On the same general principle which saves power by the use of low-speed motors and high gear ratios; namely, more efficient acceleration. In Fig. 9, the rheostatic losses with field control are less than for the same speed with ordinary control, because field control is used in series in place of the last resistance step. Fig. 6 shows the speed and tractive effort curves of a 40-h.p. field control motor with maximum gear ratio and 33-in. wheels. Fig. 7 shows the characteristics of the corresponding low-speed motor without field control, and Fig. 8, the corresponding light-weight motor. From these curves it is seen that the speed of the field control motor on normal field is about the same as that of the low-speed motor without field control, while the speed of the field control motor on full field is very low. The full field is used in accelerating and therefore the rheostatic losses are greatly reduced. The normal speed is used for running and enables the car to attain the same speeds as with the non-field control motor, so that the braking losses are not increased.

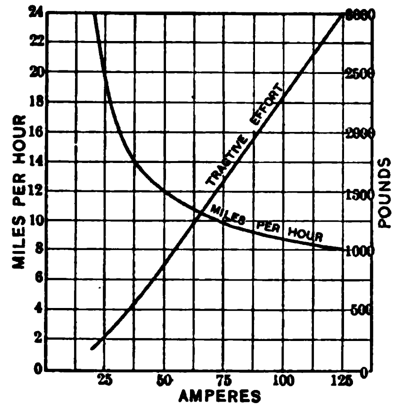

FIG. 7—STANDARD 40-H.P. MOTOR—5.12 GEAR RATIO—33-IN. WHEELS —500 VOLTS

The following example will serve to show the saving which may be obtained by field control. Suppose that the tractive effort per motor required to give the necessary acceleration is 1575 lb. With a non-field control motor this takes 75 amperes and with a field control motor only 68.5 amperes. The rheostatic losses are all cut out at 8.9 mi. per hr. with field control motor, but are not cut out until a speed of 9.9 mi. per hr. is reached with the non-field control motor. Reference to the general curve Fig. 9 will show that the corresponding rheostatic losses are 1.07 watt-hours per ton with the field control motor and 1.62 watt-hours per ton with the non-field control motor. In other words, the field control motor saves 0.55 watt-hours per ton every time the car starts. If the car weighs 30 tons and makes 9 stops and starts per mile, the saving is 0.149 kw-hr. per car-mile.

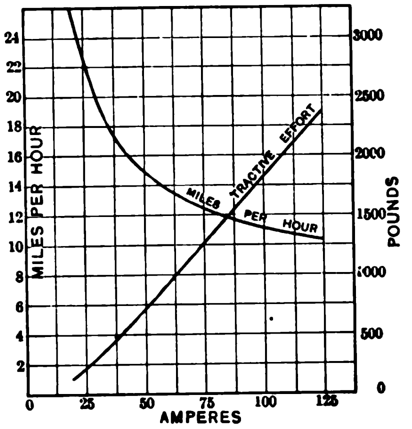

Fig. 8—Light Weight 40-h.p. Motor—5.12 Gear Ratio—33-in. Wheels—500 Volts

Fig. 3 shows the same run as in Figs. 1 and 2 made with the same acceleration as used for the low-speed motor in Fig. 2. Table I gives the results from Figs. 1, 2, and 3. The power consumed is 3.39 kw-hr. per car-mile or 9.6 per cent less than with the low-speed motor of Fig. 2 and 19.5 per cent less than with the high-speed motor of Fig. 1. In this case, the use of a low-speed motor instead of a high-speed motor reduces power consumption 10.9 per cent while the use of field control makes a further reduction of 9.6 per cent, and the combination of slow-speed motor and field control produces a saving of 19.5 per cent.

For a combined city and suburban service, similar results are obtained. The application of field control to the example of this class previously considered under Section II, shows that the field control motor will make the trip with 35.76 kw-hr. and therefore will save 10.4 per cent of the power used by the low-speed motor and 15.9 per cent of that required by the high-speed motor.

TABLE I

Length of run—ft.	587	1056
Time of run—sec.	43.4	61
Stops per mile	9	5
Length of stop—sec.	7	7
Schedule speed—mi. per hr.	9.2	11.8
Braking rate—mi. per hr. per sec.	1.25	1.25
Motor equipment	4-40 h.p.	4-40 h.p.
Gear ratio—33-in. wheels	5.12	5.12

Motor type	Light weight	Standard	Field control	Light weight	Standard	Field control
Motor rev. per min. at 40 h.p. at 500 volts	608	526	445	608	526	445
Amperes at full load of motor.	72	72	73	72	72	73
Car weight—equipped and loaded—tons	29	30	30	29	30	30
Accelerating current—amperes per motor	75	75	68.5	75	75	68.5
Accelerating rate—mi. per hr. per sec.	1.5	1.88	1.88	1.5	1.88	1.88
Speed at which rheostats are all out	12.4	9.9	8.9	12.4	9.9	8.9
Coasting time—sec.	7.5	7.5	10.8	19.8	13.3	20.8
Speed at time brakes are applied—mi. per hr.	16.2	15	14.5	15.3	16	14.7
Watt-hr. per ton-mile	145	125	113	99.3	96.7	85.7
R.m.s. amperes per motor	38.3	33.3	32.4	33.9	30.4	29.7
Temp. rise in service from air 25 deg. cent.	65	47	45	50	42	40
Kw-hr. per car-mile	4.21	3.75	3.39	2.88	2.90	2.57

For interurban service, field control produces more economical running over the low-speed city sections, permits the use of a gear ratio which is economical for local service, and with the same gearing gives a higher limited speed than could be obtained with the same size non-field control motor geared for the local schedule. This tends not only toward economy in local service, but also towards reducing the motor capacity required for the operation of frequent-stop local service and high-speed limited service with the same gear ratio.

A 75-h.p. field control motor geared for local service, as heretofore described, and operating as shown in Fig. 10, will maintain a limited schedule speed of 38.4 mi. per hr., which is the same as that possible with the next size larger non-field control motor. At the same time the reduction in power consumption is 15.9 per cent for local service and 11.7 per cent for limited service. The power consumption in limited service is somewhat more than with the ordinary 75-h.p. motor on account of the faster schedule speed maintained with the field control motor. The comparative results are shown in Table II.

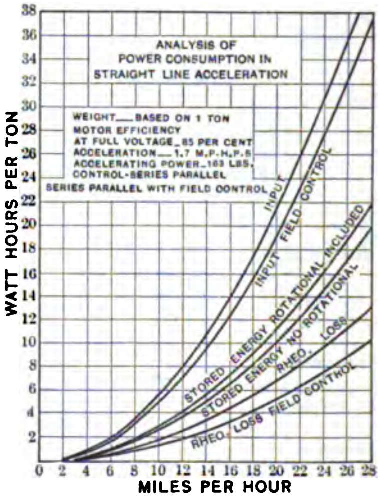

FIG. 9

V. RESULTS OF TESTS

Within the last few years, a number of tests have been made on cars operating in regular service, the results of which show that our contentions in respect to proper gearing and armature speed, correct operation and field control are correct in practise as well as in theory.

Table IV shows the results of tests made in December, 1910, under the direction of the writer, on the Frankstown Avenue line of the Pittsburgh Railways Company. The cars and equipments in this case were identical except for gear ratio.

Test A was made with a low-speed gearing, while test B was made with a higher-speed gearing. A comparison of the service conditions shows that they were approximately the same —the slightly higher schedule speed in test B being balanced by the somewhat fewer stops and slow-downs, shorter duration of stop and decreased average passenger load. The railway company had in service a number of cars equipped as for test B.

The car geared as for test A was operated in regular service for a considerable period of time prior to the tests and proved itself capable of maintaining the schedule equally as well as the car geared for higher speed. It will be noted that not only did the tests show that the low-speed gearing effected a saving of 13.8 per cent in the power consumption, but they also showed that, whereas the equipments with the high-speed gearing were operating with dangerous temperature rise, with the low-speed gearing the heating of the motors was just within safe limits. All equipments of these same motors installed since these tests were made, have been provided with the low-speed gears.

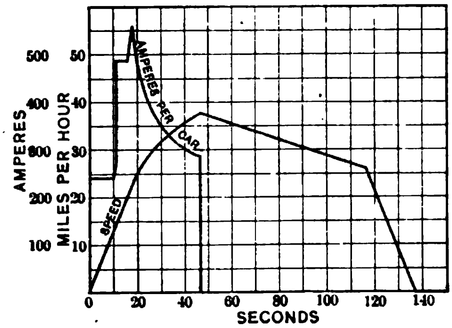

Fig. 10

In volume XXIX, p. 1484 of the A.I.E.E. Transactions, 1910, Mr. H. St.Clair Putnam makes the following statement regarding the use of coasting clocks on the Manhattan Elevated Railway in New York: " The result of these calculations and tests shows that an increase in the percentage of coasting from 12 per cent to 37.5 per cent will effect a saving of 24 per cent in the power required for traction."

The report of tests made on cars of the Chicago Railways Company, as given in the *Electric Railway Journal*, volume XXXVII, pages 1192 and 1200, shows that increasing the accelerating and braking rates (through the use of coasting clocks) will save 15.6 per cent of the power required for traction without special effort on the part of the motorman, and that it is possible and practicable to increase this saving to 27 per cent. This report also shows that there is a saving in brake shoes amounting to 40.8 per cent.

Both of the above reports show what can be accomplished by correct operation as induced by the application of coasting time recorders. It should be noted in connection with the Chicago Railways Company service that the equipments now maintain the schedule so easily that the gearing is being changed from 4.06 to 4.73 in order to reduce the peak demands. Incidentally it may be noted that one of the dangers previously mentioned in connection with the application of coasting clocks is beginning to show itself here, as the Chicago report states that the running time for the cars on the line tested has been reduced three minutes. In any such case, care should be exercised to determine

TABLE II

Length of run—miles		1			6	
Time of run—seconds	150	150	150	611.8	563	563
Length of stop—seconds	12.5	12.5	12.5	60	60	60
Schedule speed—mi. per hr.	24	24	24	35.3	38.4	38.4
Accelerating rate—mi. per hr. per sec.	1.25	1.25	1.25	1.25	1.25	1.25
Braking rate—mi. per hr. per sec.	1.25	1.25	1.25	1.25	1.25	1.25
Motor equipment	4-75 h.p.	4-75 h.p.	4-90 h.p.	4-75 h.p.	4-75 h.p.	4-90 h.p.
Motor type	Standard	Field control	Standard	Standard	Field control	Standard
Amperes at full load of motor	130	130	156	130	130	156
Car weight—equipped and loaded—tons	38	38	39.5	38	38	39.5
Accelerating current—amperes per motor	127	122	177.5	127	122	177.5
Speed at which rheostats are all out—mi. per hr.	21.3	20.3	28.2	21.3	20.3	28.2
Coasting time—seconds	60	70	77.5	67.8	86.2	86.7
Speed at which brakes are applied	27.1	26	25.7	30	30	30
Kw-hr. per car-mile	2.4	2.27	2.70	2.025	2.11	2.39
Watt-hr. per ton-mile	63.2	59.7	68.4	53.4	55.5	60.5
Temp. rise in service from air 25 deg. cent.	58°C.	60°C.	70°C.	50°C.	58°C.	60°C.

TABLE III

TESTS IN NEW YORK SHOWING EFFECT OF GEAR RATIO AND FIELD CONTROL ON POWER CONSUMPTION

Test number	Weight of loaded car, tons	Motor	Rev. per min. 40 h.p.	Gear ratio	Stops per mile	Slow-downs per mile	Average length of stop sec.	Schedule speed miles per hr.	Average volts	Watt-hr. per ton-mile	Remarks
1	20.214	Standard 60 h.p.	560	4.6	6.975	2.86	8.503	7.126	557	152.26	
2	19.729	Standard 40 h.p.	550	5.12	6.778	3.08	7.765	7.261	556	141.63	Normal field on field control motor. In congested district ran in series only.
3	20.153	Field control 40h.p.	445	5.12	8.333	3.11	7.240	7.142	551	133.85	
4	19.714	Field control 40h.p.	445	5.12	6.881	3.56	7.335	7.409	555	124.41	

2—Saves 7 per cent of power used by 1—Reason, 12 per cent less car speed at 40 h.p.
3— " 5.5 per cent " " " 2— " field control.
4— " 7 per cent " " " 3— " fewer stops.

4—Saves 12 per cent of power used by 2—Reason, field control.

what effect upon the heating of the motors such a reduction in running time may produce before faster schedules are adopted generally. More or less protection against too rapid acceleration may be secured by careful circuit breaker adjustments or automatic acceleration, or by a graduated scale with respect to the bonus offered motormen in connection with their coasting time records.

Table III shows the result of a series of tests made on the cars of the Metropolitan Street Railway Company of New York under the direction of Mr. H. H. Adams. It will be seen from this table, by comparing tests 1 and 2, that the use of a lower-speed armature and greater gear reduction effected a power saving of 7 per cent. In test 3, throughout the congested district the equipments were operated in series only and then operated in series and parallel on the remainder of the runs. In spite of the fact that this test shows nearly 23 per cent more stops than test 2, the power consumption was decreased 5.5 per cent due to the use of field control.

TABLE IV

TESTS ON FRANKSTOWN AVE. LINE OF PITTSBURGH RAILWAYS COMPANY

Showing effect of gear ratio on power consumption and motor heating.

Items	A	B
Weight of motor car without load—lb.	49,000	49,000
Weight of trailer car without load—lb.	23,000	23,000
Motors	4-50 h.p.	4-50 h.p.
Gear ratio—33-in. wheels	4.6	3.67
Schedule speed—mi. per hr.	9.15	9.50
Stops per mile	8.7	8.63
Slow-downs per mile	1.94	1.37
Average duration of stop—sec.	6.8	6.2
Average passenger load	37	30
Average voltage	483	480
Watt-hours per ton-mile	137	159
Average temperature rise on armatures corrected to 25 deg. cent. air temperature	68.8	87.8

A saves 13.8 per cent of the power used by *B;* reason—correct gearing. Day's service consisted in each case of two round trips with trailer, then three round trips without trailer, followed by two round trips with trailer.

In test 4 the number of stops and other service conditions are practically the same as in tests 1 and 2, but the motors were operated making full use of the field control in series and parallel over the entire line. This test showed 7 per cent less power consumption than test 3 with its greater number of stops, and

12 per cent saving in power in comparison with test 2, where the service conditions were practically the same. Substantially all of this saving was due to the use of the field control motor in test 4 as against the non-field control motor in test 2. In this connection, it should be noted that while the 60-h.p. motors of test 1 showed an average temperature rise of about 48 deg. cent. corrected to air at 25 deg. cent., the 40-h.p. motors in test 4 showed only 58 deg. cent. temperature rise, which is still a perfectly safe operating condition.

Tests recently made on various lines of the Pacific Electric Railway showed an average power consumption of 97.3 watt-hours per ton-mile with quadruple 75-h.p., 650-rev. per min. motors geared 2.18:1. Other 75-h.p., 640-rev. per min. motors geared 3.24:1 showed an average power consumption of 87 watt-hours per ton-mile. The latter motor with field control showed an average power consumption of 81 watt-hours per ton-mile. These figures indicate that proper gearing would effect a power saving of 10.6 per cent in this service, while the application of field control would produce a further saving of about 6.9 per cent, and the total saving which could be obtained by the use of correct gearing in combination with field control would be about 16.8 per cent. It is interesting to note further in this connection that the average temperature rise of the motors, corrected to air at 25 deg. cent., in the most severe service was 80.5 deg. cent. for the motors geared for high speed and 61.2 deg. cent. for the field control motors. Temperatures on the non-field control motor geared for low speed in this service are not available at the present time.

Summing up the results of calculations and tests as previously described in detail, it is found that proper gearing and armature speed, correct operation and field control are essential to the most economical operation of railway service and the indications are that from 10 per cent to 30 per cent of the power now consumed in specific cases may be saved by a careful study of the operating conditions and the intelligent application of these principles.

A paper presented at the April 5th Meeting, New York, and discussed at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 26-27, 1912.

THE RELATION OF CENTRAL STATION GENERATION TO RAILWAY ELECTRIFICATION

BY SAMUEL INSULL

I am not going to discuss the question of the practicability of steam railroad electrification. That is not a matter at all within my province. That is a matter that has to be decided by those great captains of industry who are in control of the vast transportation companies in this country from the Atlantic to the Pacific. But it is reasonable, as a central station man, that I should assume that the electrification of steam railroads has come to stay, that the work done by the two premier trunk lines centering in New York is a sufficient indication of what we may expect in the future. I am not in sympathy with an agitation to force the steam railroads in this country to electrify. That is a question of the provision of the capital necessary for the purpose, and that question must be taken up and settled by those who are responsible for the operation of the railway properties. Nor am I going to discuss what might be termed the technique of the electrification of steam railroads; that is, the special system that should be used, whether it should be done with one class of current or another, or one pressure or another. The system finally decided on must be the one which fills conditions of railroad operation, and at the same time renders it possible for the railroad company to take advantage of the sources of energy supply already existing, as the railroad demand is only about 15 to 20 per cent of the total demand for energy in any community. That amount of energy which the railroads require to operate their properties is really the thing that should turn them to central station men for assistance, and I speak as a central station man.

The amount of energy required to operate the terminal and suburban systems of all the trunk lines centering in and around New York City (as I think I will be able to demonstrate to you) is, I believe, less than the amount of energy required to operate the isolated electric lighting plants in the same territory. It is not a serious proposition. To my mind it is of less consequence to the properly operated electricity supply company than the isolated plant business was to the electric light and power companies through the country twenty years ago, or even fifteen or ten years ago.

The problem of the relation of the central station to the generation and primary distribution of energy, so far as the steam railroads are concerned, is a question of economics. It cannot properly be considered without taking into account the entire question of generation and primary distribution for any given center of population. If you consider steam railroad electrification by itself, the amount of energy required seems to be very great indeed. If you consider it merely as a fraction of the supply of energy required by a community for all kinds of purposes, it is found to be simply an incident. Perhaps a more accurate title for this paper would be " The Generation and Primary Distribution of Energy for Given Areas," because that is the real question involved. It is not a new subject; it is a subject dealt with at great length in the inaugural address of 1910 by my friend Mr. de Ferranti, when addressing our sister organization, the British Institution of Electrical Engineers. Mr. de Ferranti went further than I am going in this discussion, and proposed a scheme of generation and distribution for the whole of Great Britain. He proposed a scheme that meant, in his opinion, a saving of 80,000,000 to 90,000,000 tons of coal a year for Great Britain. If the plan, which you must necessarily admit is reasonable, after studying the maps and curves presented, were adopted, my judgment is that it would mean the greatest conservation of one of the most important natural resources of this country, namely fuel, to the extent, probably, of from 100,000,000 to 150,000,000 tons of coal per year.

The method of concentration of generation and distribution of primary power, as I said, is not a new subject. It has been an absolute necessity in all the smaller communities of this country. First, in the small communities they formed companies to do the public lighting; next they added to that the incandescent lighting business, a little later they added the power business, then they connected up two or three small towns together, and to-day the average prosperous small local company supplies energy not only for lighting, whether for domestic or commercial or public purposes, but for power, for pumping water, and for the urban and interurban transportation, and as a result has raised its load factor from about 20 per cent, when it was engaged solely in the lighting business, to from 40 to 50 per cent to-day. That method of concentration of generation is going on to such an extent in the smaller communities throughout this country that I know of cases where, in an area of 15,000 square miles, that is, an area 150 miles one way by 100 miles another way, they seriously have in contemplation doing away with possibly 100 to 120 generating stations, and replacing them with ten or twelve stations.

Where there are large water powers adjacent to the larger cities, you find no hesitation on the part of the railway company, the electric light and power company, and the electrified steam railway company, if there be such, in that vicinity, in taking the energy from one source of supply. Is there any reason why the power generated at Niagara Falls can be used alike by all these enterprises, whether they be local public service enterprises, state public service enterprises, or interstate enterprises—is there any peculiarity about the fact that the power is generated hydraulically? Is that any special reason why these various industries should all take their energy from a given source? Is it not just as reasonable that they should all take their energy from a given source, if that power is supplied from fuel, from coal, with steam turbines as the prime movers, as that they should do this when the power is supplied from water with hydraulic turbines as prime movers? I cannot see any reason, if concentration of production is the correct principle in one case, why concentration of prôduction is not the correct principle in every case.

I have naturally taken for the purposes of my discussion the information which the engineers of public service enterprises in New York have placed at my disposal, together with the information that I naturally am able to obtain from my own operations in Chicago, and the conclusion that I have come to is that the concentration of the production of energy, for all purposes required in a given area about any large center of population, would result in such a saving in capital, and such a saving in operating expenses, as to provide sufficiently for the generating capacity and primary transmission systems necessary to electrify the terminal systems and suburban service of all the trunk lines centering in and around that center of population, (particularly is this true of New York) and such a saving as to yield very large profits, in addition, to the engineers and financiers having the courage to handle so great a problem.

The *percentage* of saving is comparatively small. On a percentage basis I may say that the percentage of saving in greater New York (by " greater New York " I include that part of the Jersey shore that would naturally be considered a part of a Greater New York,) is comparatively small, and to my mind somewhat disappointing, owing to peculiar conditions which I will explain later. But the saving itself is so large and amounts to such a vast sum of money, capitalized, that I cannot see how it is possible, whatever may be the jealousies of management, and whatever may be the individual interests of the financial people operating the various properties,— both as engineers desiring to get the greatest possible results out of their work, and as capitalists wanting to supply the greatest possible amount of service at the lowest possible cost to the public and the greatest possible profit to themselves, I cannot see how either the engineers or the financiers can neglect the subject and let it pass by, as it is one of the greatest opportunities I know of in our business.

To take up now the illustrative curves, Fig. 1 is the New York total load diagram. It includes the present electrical load of the central stations in Greater New York and the central stations on the Jersey shore, within a radius of ten or twelve miles of New York, operated by the Public Service Corporation of New Jersey, and the station of the Hudson and Manhattan Railroad Company.

The diagram includes only that portion of the load of the electrified steam roads which has already been electrified, and does not include an estimate of the load of the isolated plants. If the balance of the load of the electrified steam roads and the isolated plant load were included, the total would be in the neighborhood of 1,000,000 kw.

Looking ahead, if you take this New York maximum of 676,000 kw. and apply an 8 per cent annual increase (the actual increase of this maximum over the previous winter was 7½ per cent), at the end of eight years the New York maximum would amount to 1,250,000 kw., and at the end of ten years to 1,480,000 kw.

If there be added to these figures the isolated plant and steam railroad demand, it makes about 1,000,000 kw. of load at the present time. The steam railroad demand would be about

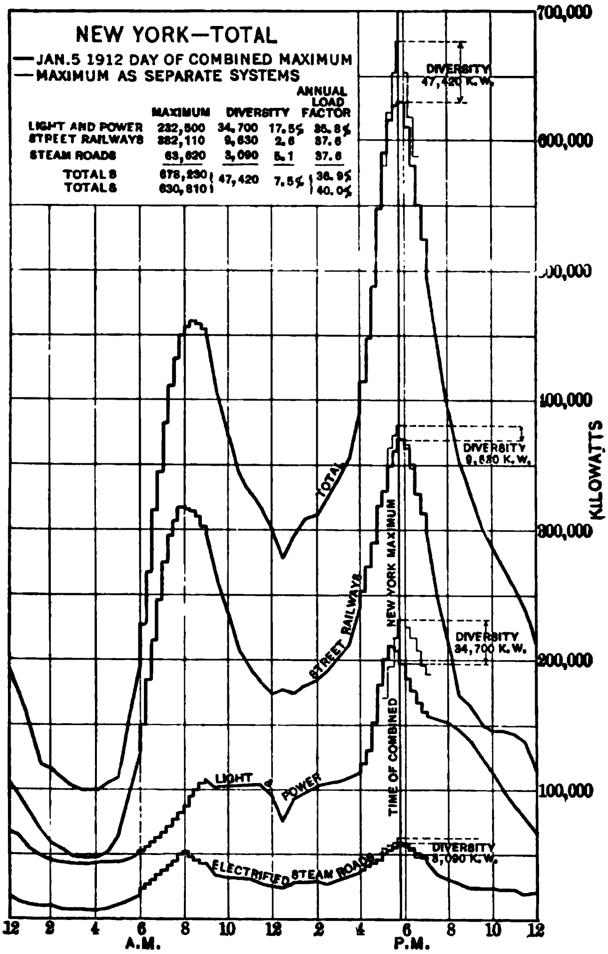

FIG. 1

170,000 kw. of that total, and the demand made by isolated plants would be 217,000 kw.

The total load of the systems separately is 678,000 kw., and there is a diversity factor that would reduce that if they were all run as one system; that is, if the present business of the lighting and power companies, the street railways and the steam railways were combined, the maximum load this last winter would have amounted to 630,000 kw., or a saving of upwards of 47,000 kw. The diversity factor amounted to 7.5 per cent, and the load factor would have been improved from 36.9 to 40 per cent.

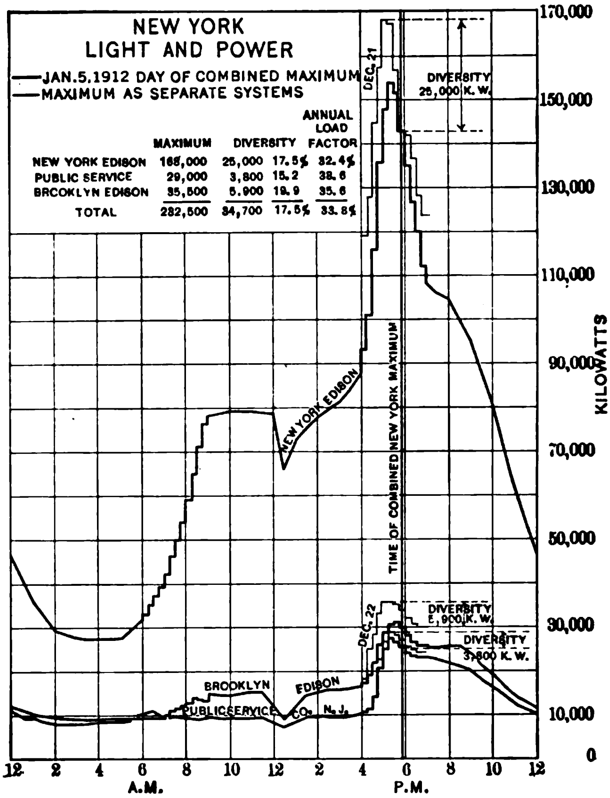

FIG. 2

Later, I will explain some of the advantages obtained from that.

Fig. 2 is the New York light and power load diagram. The New York Edison Company curve includes the load of the United Electric Light and Power Company and also the Bronx load. The Public Service Corporation curve includes that company's light and power load only, its street railway load being on the street railway curve.

The total load is 232,500 kw. The load factor of the various systems by themselves is 33.8 per cent. There is a diversity of 17.5 per cent, amounting to 34,700 kw., between the sum of the maxima for the year of these different lighting companies and their load between 5:45 and 6 p.m. on January 5, 1912, which was the time of the maximum for all of the New York companies combined, that is, the lighting, the street railway and the electrified steam railroad companies.

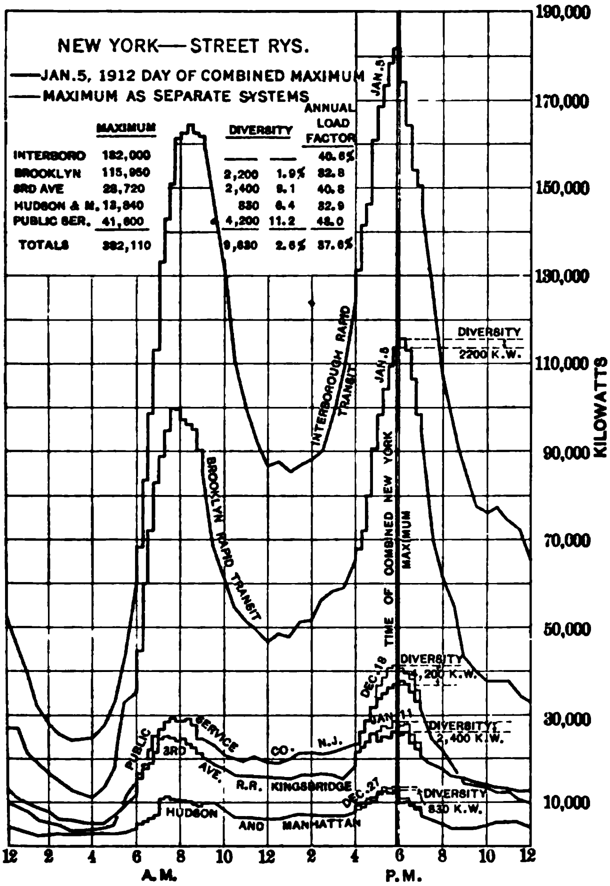

FIG. 3

Fig. 3 shows the load diagram of the street railways of New York City. The Interborough has much the largest maximum of any of the New York companies, and therefore establishes the day and hour of the combined maximum, and there is no diversity between the Interborough load and the combined maximum. The diversity between the three power houses, subway, surface and elevated, of the Interborough has not been taken advantage of, and possibly amounts to a considerable figure. What is meant by that is that I have not taken advantage of it in making these diagrams, because the interests having charge of the street railways, I believe, have already taken advantage of it by connecting up their various power houses, so as to get the advantage of the diversity factor.

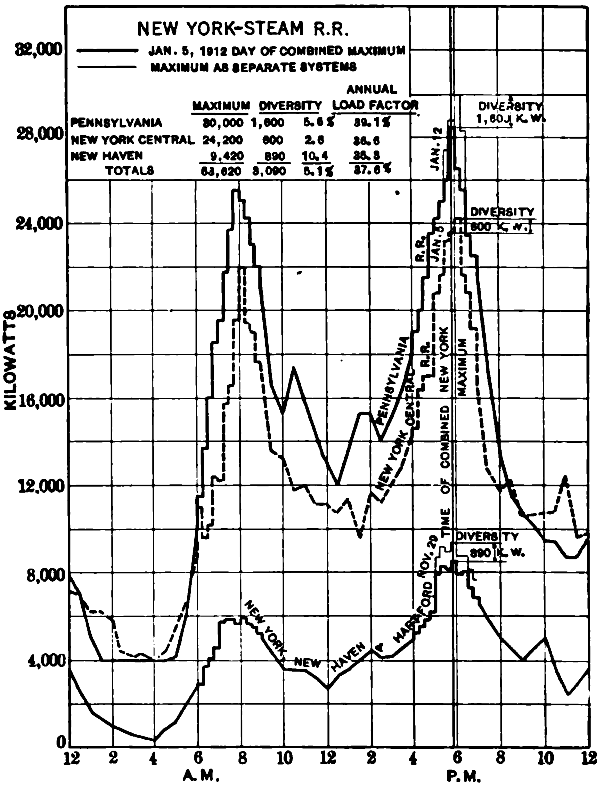

FIG. 4

Fig. 4 shows the load diagram of the steam railroads entering New York City. Due to the electric heating of the suburban cars, the New York Central maximum occurs on the same day as the Interborough and the combined maximum, and the Pennsylvania maximum, for the same reason, only a few days later.

The present electrical load for the passenger service of the steam railroads of New York is estimated at about two-thirds of the total load if all of the passenger service within a reasonable radius of say fifteen to twenty miles of New York City were electrified. This would give for New York a total electrified passenger load of 95,000 kw., as compared with our estimate for Chicago of 73,000 kw., which appears reasonable. If to this we add 75,000 kw. for freight, as compared with our estimate for Chicago freight of 78,000 kw., we get a total for the electrified steam railroads in the vicinity of New York of 170,000 kw.

Attention might be called to the fact that the farther out the steam railroads are electrified, the less influence the suburban service will have and therefore the greater the diversity factor.

There is a very important point I wish to emphasize, that has a bearing on this subject only in the large centers of population where there is heavy suburban travel. The same thing will be shown in some of the curves to follow. These two maximum loads, morning and evening, are made up of suburban business, and the suburban railway load maxima are largely affected by the heating proposition, and also the large amount of power needed additionally for traction in cold weather. That condition cannot possibly exist except in a few, perhaps a dozen different cities of the United States. The steam railroad load factor is relatively poor in those centers, but if you will take the average business throughout the country where our central stations are in cities, say of the second and third grade, the steam railroad load would show a very much better load factor, as there is practically little or no suburban business in any cities except the very largest cities of the country.

Fig. 5 is the total load diagram of Boston. The street railway curve is the Boston Elevated Railway Company load, which includes the subway, surface and elevated roads. The Edison light and power load is also given.

A careful estimate of the electrical requirements for the passenger service only, for all the steam roads operating within the metropolitan district of Boston, has been made, but as the figures do not include freight, and also for the reason that the larger portion of it is based on 11,000-volt single-phase operation, which system practically eliminates the possibility of showing savings in transmission and substation by combining with the other local power supply, I have not attempted to include load curves for the electrified steam roads. Also no estimate has been made of the isolated plant load in Boston. The total capacity of the Boston steam plants, 160,600 kw., amounts to a reserve on the combined load of 68 per cent.

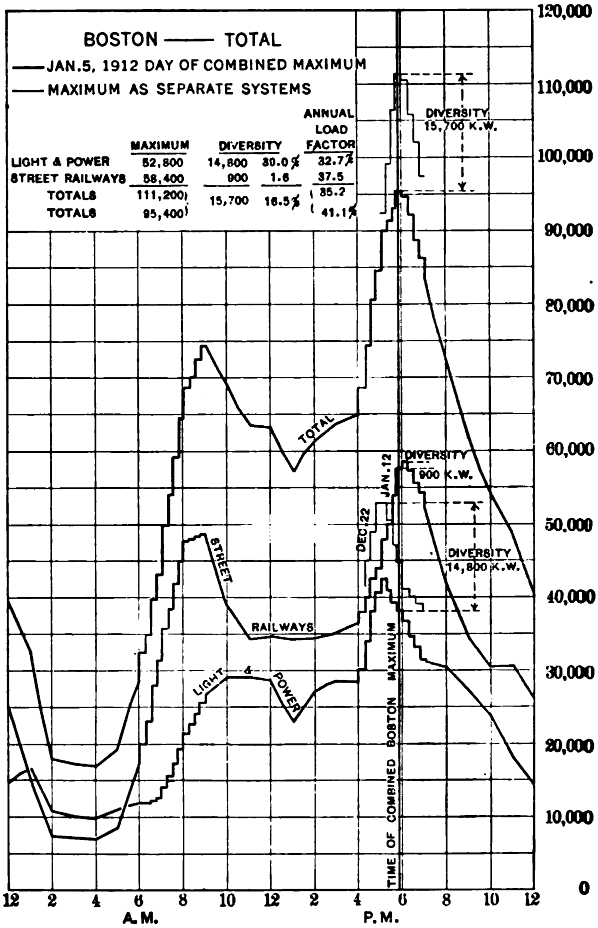

Fig. 5

It will easily be seen that there is a remarkable diversity between the loads of the street railway and lighting and power companies in Boston. To me it seems almost incredible that there should be built a second large power station in Boston, when, if the service for both the lighting and railway were run by the same station, the maximum load last winter would have

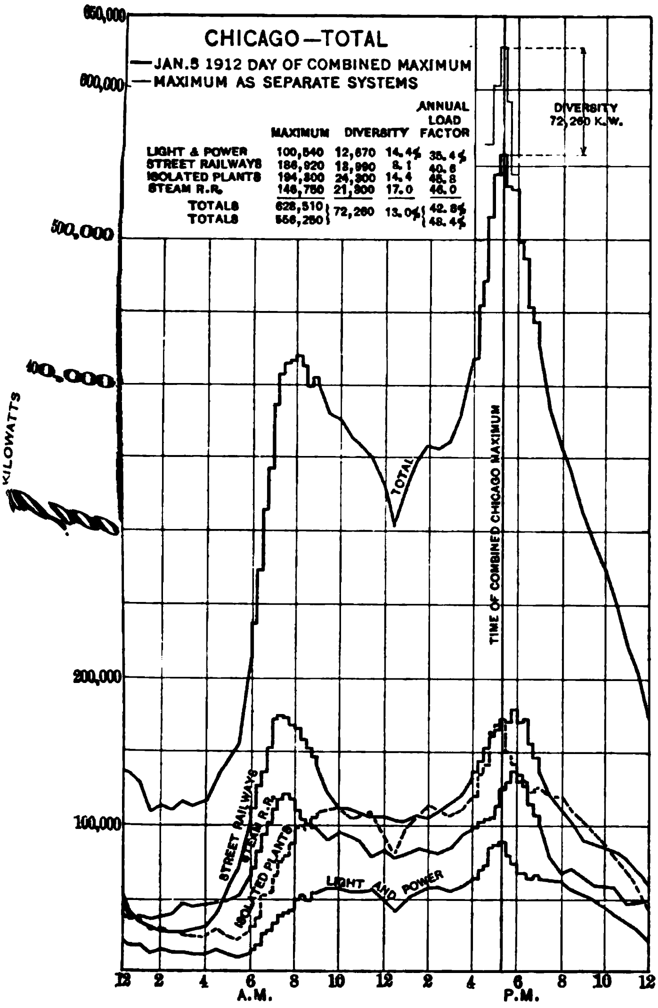

Fig. 6

been 95,400 kw., instead of 111,200 kw., as there is a diversity of 16.5 per cent between the two businesses.

Fig. 6 shows the total load diagram for Chicago. The diversity shown in the tabulation on this chart amounts to 72,260 kw., and would require, assuming a 25 per cent reserve, 90,300 kw. more capacity if operated as separate systems than if operated on a combined generating system. At $75 per kw. this amounts to an extra investment of $6,772,500.

The isolated plant load, although showing a maximum 50 per cent greater than our present light and power load, I believe has been estimated conservatively low. A canvass of the number and size of isolated plants was made by the contract department of the Commonwealth Edison Company, and several checks on these figures were available, such as " The Engineers' Directory," the agents' knowledge of the field and the City of Chicago Boiler Inspectors' records.

In estimating this isolated plant load, the separate maxima of the plants are assumed to be two-thirds of the rated capacity, and the load factor, that is, the ratio of the average kilowatts for the year to the maximum kilowatts, is assumed to be 25 per cent, the assumption being based on the fact that the actual load factor of customers on our wholesale schedule, representing a very large amount of business, is 26 per cent.

On account of the diversity between the different isolated plants, it is assumed that their load factor, if combined, would be equal to the load factor of the Commonwealth Edison Company's general light and power business, that is, 35.5 per cent.

To the maximum kilowatts and kilowatt-hours thus obtained are added a certain portion of the South Chicago Steel Works load, the refrigeration load, assuming that one-half the ice of Chicago is produced electrically, and the electric vehicle load, assuming two-thirds of all horses replaced by electric vehicles. These latter two items, being off-peak loads, improve the load factor up to the figure shown, although they represent only 17 per cent of the total estimated kilowatt-hours of the isolated plants.

The increased investment necessary as between these systems being operated all as one, including steam railways, and being operated as separate systems, taking the cost of generating plant plus the cost of the primary transmission system, would mean an expenditure of upwards of $10,000,000 to $12,000,000 more than if the work is done on one system. We have got reasonably well started in Chicago towards doing it on one system. We have practically the most important part of the work, that is, the street railway work, and we are trying there to do all we can to get the isolated plants out of existence, and in the steam railroad business, as may be seen from our estimates, in what is the greatest railroad center in the United States to-day, passenger, freight and transfer business combined, the amount of energy required for operating all of the terminal systems there is so small a percentage of the whole that it would seem unreasonable to think we will not be able to get that, certainly in Chicago, as well as the business of the surface and elevated railroads.

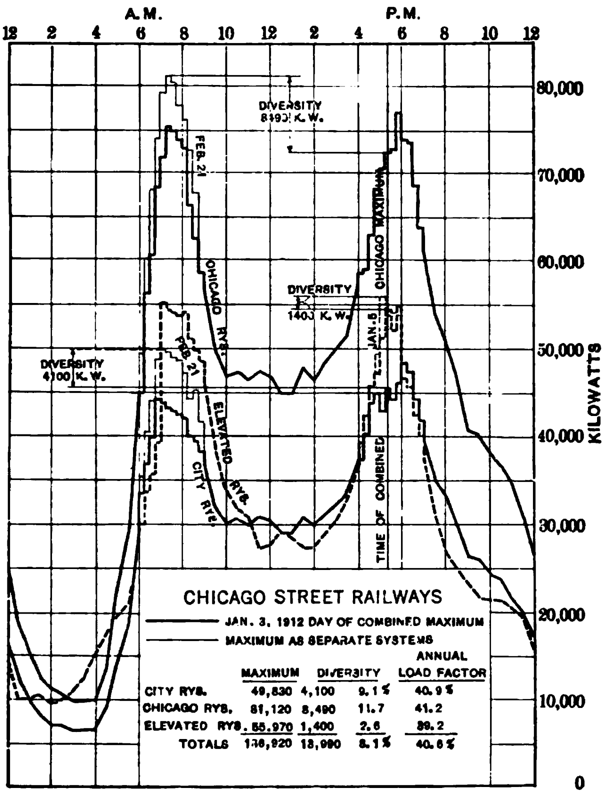

FIG. 7

The next diagram, Fig. 7, shows the load curve of the street railways of the city of Chicago. One interesting feature of this chart is that the highest maximum for two of the street railway companies occurred in the morning of February 21st, soon after the beginning of a very heavy snow storm, with a strong cold wind blowing and the temperature a little above 20 deg. fahr.

That chart is generally characteristic of the urban transportation business of a city of the size of Chicago.

Fig. 8 shows the load diagram of the electrified steam railroads of Chicago, assuming that the steam railroads in the vicinity of Chicago are electrified some time. It is a load diagram of the maximum for the year. The method of estimating all of the data regarding the load of the electrified steam roads of Chicago is given in detail in the appendix to this paper, on "Electric Power Requirements of the Electrified Steam Railroads of Chicago," prepared by Messrs. Bird, Gear and Fowler.

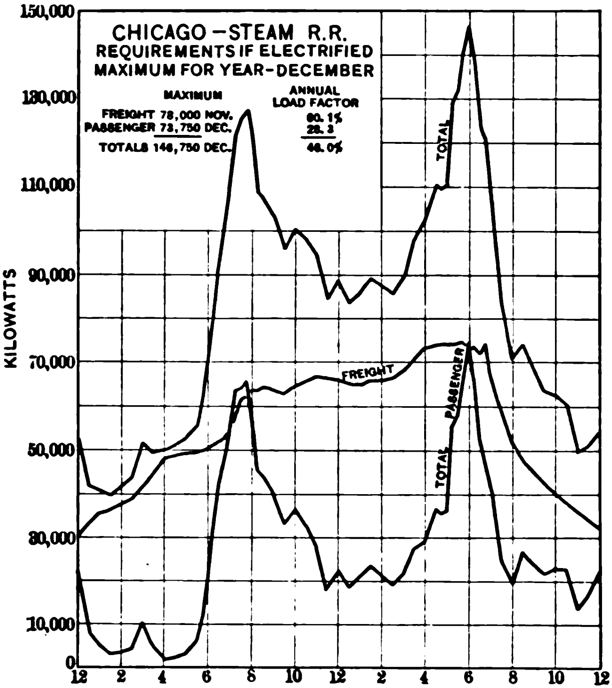

Fig. 8

The freight curve, you will see, has an extremely good load factor. The passenger business is governed by exactly the same conditions, only intensified, that govern the passenger business in New York City. I presume the curves of passenger business in New York, Chicago, Boston and Philadelphia would probably be all about the same, except that Philadelphia, Boston and New

York ought to have some advantage from a much larger amount of pleasure business in the summer than we get in Chicago.

The extreme peak in the morning and evening is caused by the suburban business, the extra amount of energy necessary at the time of extreme cold for traction purposes and the extra amount of energy necessary for heating purposes. If it were not for these two peaks, the load factor would even up better than it does, and yet, notwithstanding these peaks, the combined freight and passenger business is estimated to have 46 per cent load factor. Now, if we consider the steam railroad business, say in cities of the size of Rochester, Detroit, Buffalo, and possibly

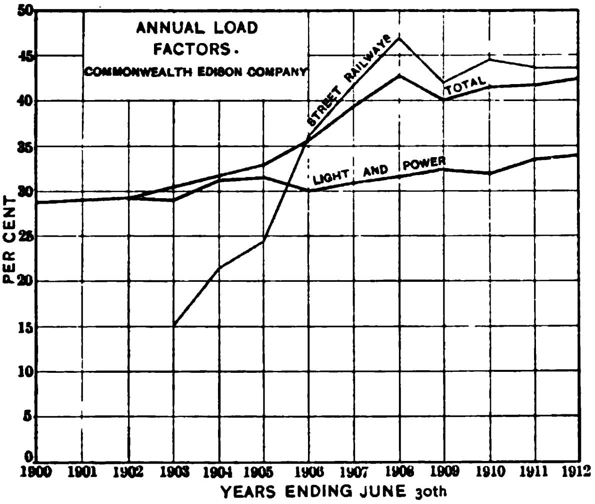

FIG. 9

Cleveland, Toledo, and similar cities, their load factors would be uniformly better than is shown in Fig. 8, and in my judgment the date of the maximum load, and the time of day of the maximum load, would probably change considerably, to the advantage of the local power company supplying the energy.

I thought it might be of interest to include a chart of the annual load factors of the Commonwealth Edison Company for the last twelve years, as shown in Fig. 9. You will notice that the street railroad load factor went up and then dropped. It was at its highest for a few years just before one of the large street railways shut down its obsolete stations, which it had operated as peak plants only, also having the result of earning it a very low price for the energy it purchased. The tendency of the railway load factor is to run even. The tendency of the light and power load factor is to run up. The combined load factor, as shown in Fig. 9, is about 42.5. The light and power business by itself has a load factor a little under 35, and the street railway business by itself about 43 per cent.

Fig. 10 shows the diversity in a block of apartments. This figure has been used a number of times, both by myself and by some of my subordinates in writing papers on different subjects where the question of diversity and load factor comes in, for it is a striking illustration of diversity. The figure shows a block composed of average apartments, all alike. The number of apartments is 225, number of customers 189, lamps per customer 10.6, the kilowatt-hours used per year 33,000, and the customers' separate maxima show only 5.5 per cent load factor. The maximum at the transformer shows 19 per cent load factor. Here are 189 customers, all living in similar apartments, all of about the same class, all with about the same habits of life, and yet the difference in the load factor, taking each customer by himself, as compared with all of them put together, is such that you get almost four times as good a load factor, and that is owing to the diversity of demand. That is the fundamental basis of the profit-making of an energy selling company. We get that average in dealing with small customers, and consequently we can sell these small customers at a profit as a whole, whereas

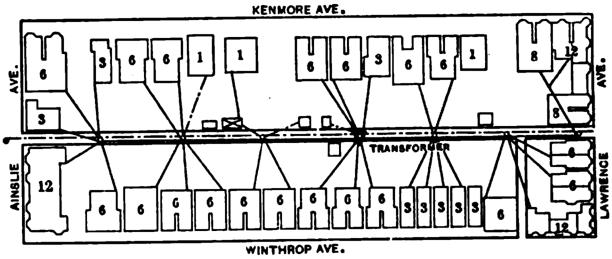

FIG.. 10—BLOCK OF APARTMENT BUILDINGS

Number of apartments....................	225	
" " customers......................	189	
" " lamps per customer.............	10.6	
Kw-hr. used per year.......................	33,000	
Customers' separate maxima...............	68.5 kw.	= 5.5 per cent load factor
Maximum at transformer..................	20 kw.	= 19 per cent load factor
Annual income per customer...............	$18.34	
Diversity factor...........................	3.4	

any engineer who knew the facts could demonstrate to me that each one by himself is a loss to us.

It is exactly that same principle—I am getting down to the fundamentals, the A, B, C, of energy production and distribution—that I and others who advocate the same ideas want to see

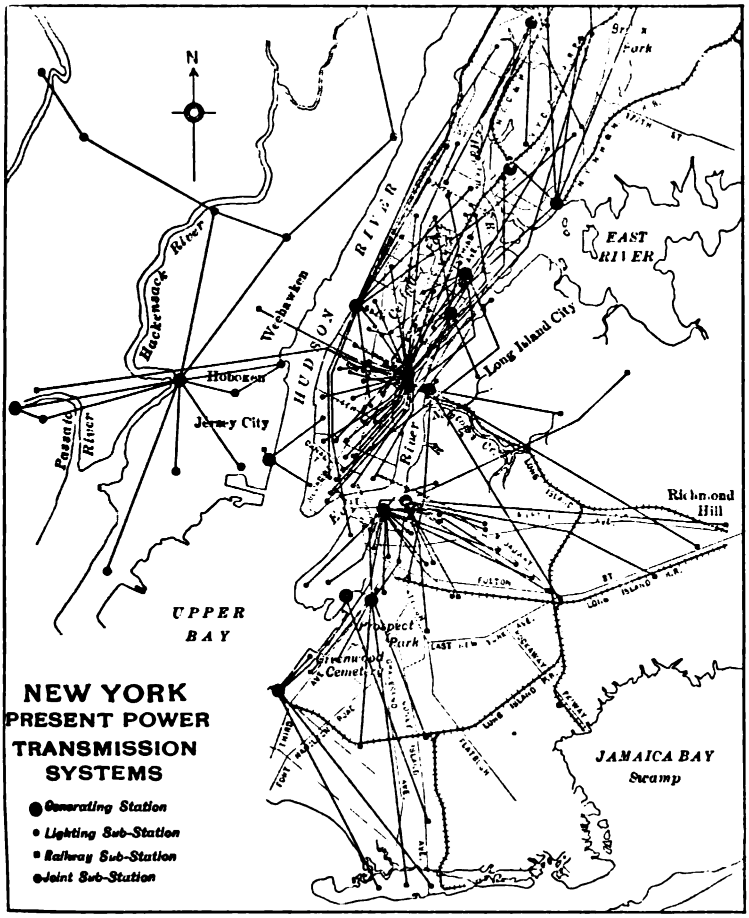

FIG. 11

applied in all the electric supply business, whether it is in large communities or small communities; and I want to see somebody get the advantage of that diversity factor that exists. In one case, with small customers, it may show 400 per cent advantage. In another case, in a vast community like the city of New York and surrounding territory, that percentage may be only ten per cent, but it runs up into millions and millions of dollars, which is being thrown away to-day, and I do not want to see those who are right on the threshold of entering into our line of business, the use of electrical energy, make mistakes owing to their ignorance of the real situation. I do not want to see them make the mistake that, in my judgment, largely through force of circumstances, the New York Central company has made in building its present power house, and the Pennsylvania Railroad Company has made in building its power house,

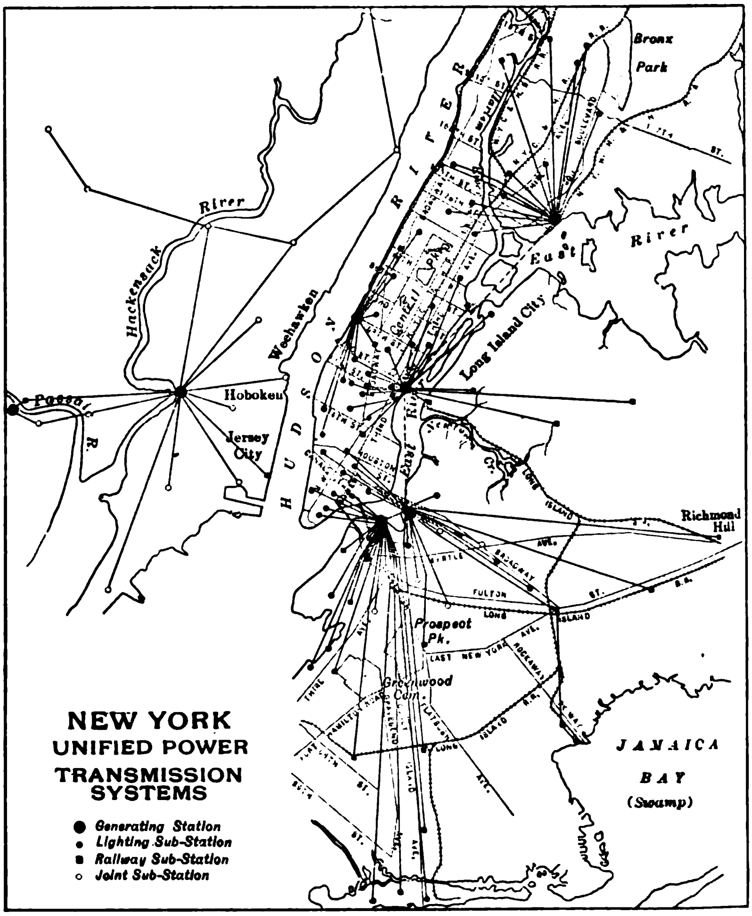

Fig. 12

probably, I think, as much because they could not find people to sell them energy as because they did not know they ought to buy energy instead of manufacturing it.

Fig. 11 is a map of New York City, with the present power transmission systems. In referring to New York City, you will notice that I go out on the Hackensack river into New Jersey, as I consider that territory properly a part of the area included in the greater city for the purposes of the present discussion.

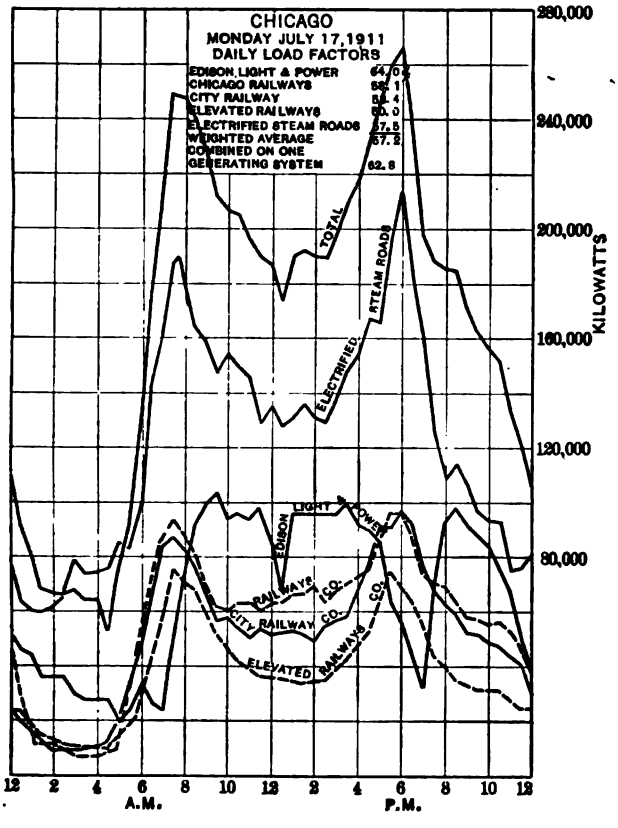

FIG. 13

Fig. 12 shows the New York power transmission system unified into one system. You will notice the difference between the two. In Fig. 11 the vast number of substations and transmission lines is in marked contrast to the effective distribution in Fig. 12.

Fig. 13 shows the Chicago daily load factor. This diagram shows the improvement in load factor as it affects operating conditions, the improvement being due mainly to the railway load coming up earlier in the morning and the depression in the light and power load at the time of the evening railway peak. It is almost impossible to figure absolutely and closely this saving from concentration of production of electric energy. It is easy enough to figure the saving of investment, but it is pretty hard to figure the saving in operating expense. It is a very large amount, indeed, and the items especially affected are the items of what one might call " readiness to serve ", including, of course, the expenses incident thereto. I do not refer to fixed charges but to operating expenses outside of fixed charges. Although it is easy to figure the saving in fixed charges due to diversity, it is not so easy to figure the saving due to the broadening out of this daily curve, but it goes a long way towards reducing the readiness-to-serve charges per unit produced in a given time.

In Table I is a tabulation of the daily load factors in Chicago. This expresses the matter a little differently. The average daily or operating load factors for the different systems operating separately, 55.6 per cent, is equivalent to thirteen and one-half hours straight-line or steady operation per day. The load factor for all combined on one generating system, 59.9 per cent, is equivalent to fourteen and one-half hours per day, or an increase of one hour, or 7.4 per cent. This improvement means that the fixed charge and " readiness-to-serve " portion of the operating expense is prorated over a greater number of units of output per day and per year.

You will notice, as shown in the table, the improvement in conditions in each month in the year. The average shows a decided improvement if the systems are combined in one. The average is 59.9 and the average of the others, separately, is 55.6 per cent.

Fig. 14 shows a diagram of the Boston daily load, and Table II is a tabulation of the Boston daily load factors. It shows that there would be quite an improvement if the Boston Elevated and the Boston Edison loads were operated together. The average is 53.9 per cent operated separately and 59.4 per cent if operated as one system.

Table III gives a tabulation of the New York daily load factors. It gives the same general character of information. Operated separately the stations show 51 per cent, and operated together 56.2 per cent.

TABLE I—CHICAGO
DAILY LOAD FACTORS

	1911 Mon. Feb. 13	Wed. Mar. 15	Sat. Apr. 15	Tue. May 16	Fri. June 16	Mon. July 17	Thur. Aug. 17	Sun. Sept. 17	Fri. Oct. 20	Mon. Nov. 20	Thur. Dec. 28	1912 Wed. Jan. 3	Average of 12 months
Commonwealth Edison Light and Power......	62.4	63.5	54.5	56.3	64.2	64	56.5	42.5	50.9	51.4	49.3	49.4	55.4
Railways Company........	58.3	54.5	58.2	54.3	53.3	58.1	52.6	61.1	53.7	52.8	53.5	56.5	55.6
City Railway Company....	57.5	52.4	55.3	49.8	48.4	53.4	49.1	66.9	51.5	61.1	60.2	57.6	55.3
Elevated Railway Company	51.5	49.8	50.7	49.9	48.5	50.3	48.8	66.3	45.7	48.3	55.7	51.7	51.4
Electrified steam railroads.	55.5	55.5	57	58.7	58.8	57.5	59.3	64.8	60.2	58.4	55.7	54.8	58
Weighted average of above	56.5	55.5	55.8	55.3	56	57.2	55	58.7	54.3	54.8	54.5	53.8	55.6
Combined on one generating system..........	60.7	59.1	64.3	57.6	62.2	62.8	59.8	61.5	56.4	58.3	58.6	57	59.9

TABLE II—BOSTON
DAILY LOAD FACTORS

	1911 Mon. Feb. 13	Wed. Mar. 15	Sat. Apr. 15	Tue. May 16	Fri. June 16	Mon. July 17	Thur. Aug. 17	Sun. Sept. 17	Fri. Oct. 20	Mon. Nov. 20	Fri. Dec. 22	1912 Fri. Jan. 12	Average of 12 months
Boston Edison............	59.2	68.2	59.6	63.9	65.7	69.5	68.8	47.4	52.5	42.6	44.2	52.8	57.9
Boston Elevated..........	51.3	52.8	56.2	48.8	51.9	48.1	49.3	70	45.9	48.4	52.7	53.3	52.4
Weighted average of above	54.5	58.6	57.5	54.6	57.2	55.5	56.7	56.2	49.5	45.6	48.4	53.1	53.9
Combined on one generating system...............	54.8	62.7	63.2	66.4	67.3	63.4	66.3	56.2	49.5	51.6	55	56.1	59.4

TABLE III—NEW YORK
DAILY LOAD FACTORS

	1911 Mon. Feb. 13	Wed. Mar. 15	Sat. Apr. 15	Tue. May 16	Fri. June 16	Mon. July 17	Thur. Aug. 17	Sun. Sept. 17	Fri. Oct. 20	Mon. Nov. 20	Thur. Dec. 21	1912 Sat. Jan. 13	Average of 12 months
New York Central.........	48.0	47.4	46.8	43.2	45.6	43.9	44.3	63	40.5	43.3	45.7	44	46.3
New York, New Haven & Hartford..............	52.4	49.8	56.2	50.9	49.5	47.2	51.2	50.1	50.3	48	48.8	53.2	50.1
Pennsylvania R. R.........	58.4	54.4	57.8	49.3	51.6	49.9	47.3	64.8	54.3	49 1	49.9	53.3	53.2
New York Edison Co......	52.1	57.6	52.8	57.2	58.5	62.2	61.7	46.8	48	42.3	44	45.7	52.4
Brooklyn Edison Co.	49.6	50.7	44.4	46.9	45.3	45.7	48	43.6	51.2	52.2	48.5	49.1	47.9
Public Service Co. (Light and power)...........	50.5	47	40	46	42.6	46.2	47.3	39.5	46.8	43.5	45.3	48.8	44.9
Public Service Co. (railway)	50.7	47	61.3	45.6	42.2	46.9	49.1	64.	50	47.4	47.3	49	50
Brooklyn Rapid Transit.....	59.7	50.6	57	48.8	48.4	52.8	49.1	66.1	45.6	48.5	50.6	46.3	52
Interborough Rapid Transit	64.2	49.8	53.3	48.1	49.6	57.5	58.5	57.8	58.5	58.5	53.5	51.5	55.1
Third Ave. R. R...........	70.6	54.7	58.5	52.8	54.5	63.3	64.3	63.5	64.3	64.3	59.1	56.6	60.5
Hudson & Manhattan.....	54.1	46.1	46.5	46.6	49.3	45.9	46.7	71.3	49.2	49	55.2	47.4	58.9
Weighted average of above.	53.4	52.8	52.7	50.7	50.3	52.2	52	54	49.5	48.1	48	48.4	51
Combined on one generating system...............	53.6	54.6	64.4	58.7	58.7	60.7	59.4	63.8	49.6	50.2	50.6	50.1	56.2

Fig. 15 is a comparison of the Chicago and New York load diagrams. In this diagram the different load curves shown have all been prorated so that the maxima of all are equal and the same as that for Chicago for January 3, 1912. This method of comparing load diagrams shows just what hours of the day are affected by the improvement in load factor, and brings out perhaps more clearly than any other method the great advantage from an operating standpoint of the combination of the energy supplied for different purposes on one generating system. This improvement, for instance, for Chicago as compared with New York, has a very decided effect upon the operating cost, and is one of the principal reasons for the very low generating cost in Chicago.

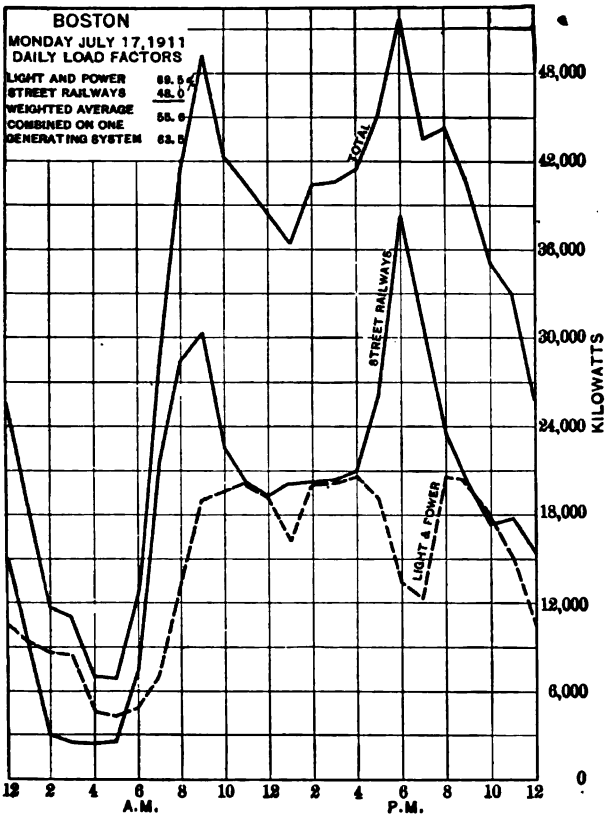

FIG. 14

The effect of diversity on the peak, which results in a saving in investment, can be and has been very readily figured. But the effect of this diversity in reducing the operating cost cannot be so readily calculated. Nevertheless, there is no doubt that the saving in operating expense is fully as important as the saving in investment.

Fig. 15 was prepared to show exactly the result of the policy the Commonwealth Edison Company has pursued in Chicago for the last ten years. It was just about ten years ago when we commenced to sell energy at prices that most of the producers of energy in this country thought were so ridiculously low that it was only a question of time and the size of our pocket-book as to how long we could stand it. This diagram shows you the result we have been able to obtain. As a contribution to our fixed charges, as a contribution to our stand-by charges, as a means of producing more kilowatt-hours in a given period, so as to provide us with the necessary funds to adopt a reasonably bold policy of selling energy, in ten years we have been able to attain this result.

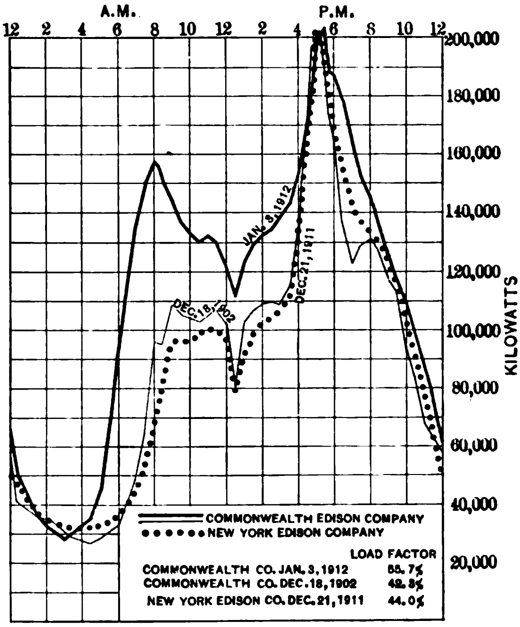

FIG. 15—NEW YORK AND CHICAGO—LOAD DIAGRAMS FOR MAXIMUM DAY OF YEAR PRORATED TO CHICAGO 1912 MAXIMUM FOR COMPARISON

Fig. 16 is a comparison of the Chicago and Boston load diagrams.

Fig. 17 is a map showing the Chicago railroad terminals in the proposed electrical zone, the boundary of which was laid out by the Chicago Association of Commerce. The zone includes a territory about 32 miles long, with an average width of ten to twelve miles.

Fig. 18 is a map of the electrification of steam railroads in Chicago,—based on a plan of group operation: that is, a plan of generating stations, substations and primary transmission lines on the theory that the railroads of the various financial groups, the New York Central group, the Pennsylvania group, and so on, would operate their power jointly, *i.e.*, that the New York Central would have a system for itself, the Pennsylvania would have a system for itself, and so on all the way down the line.

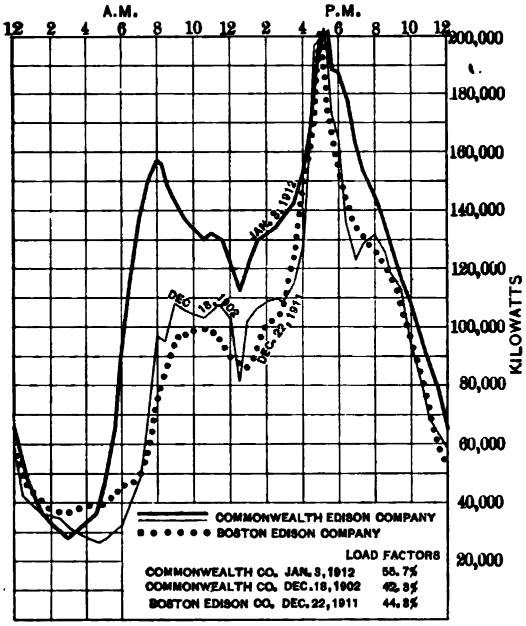

Fig. 16—Boston and Chicago—Load Diagrams for Maximum Day of Year Prorated to Chicago 1912 Maximum for Comparison

Fig. 19 shows the electrification of steam railroads, with unified power supply, in the city of Chicago. That is what it would be like if all the companies obtained their power from

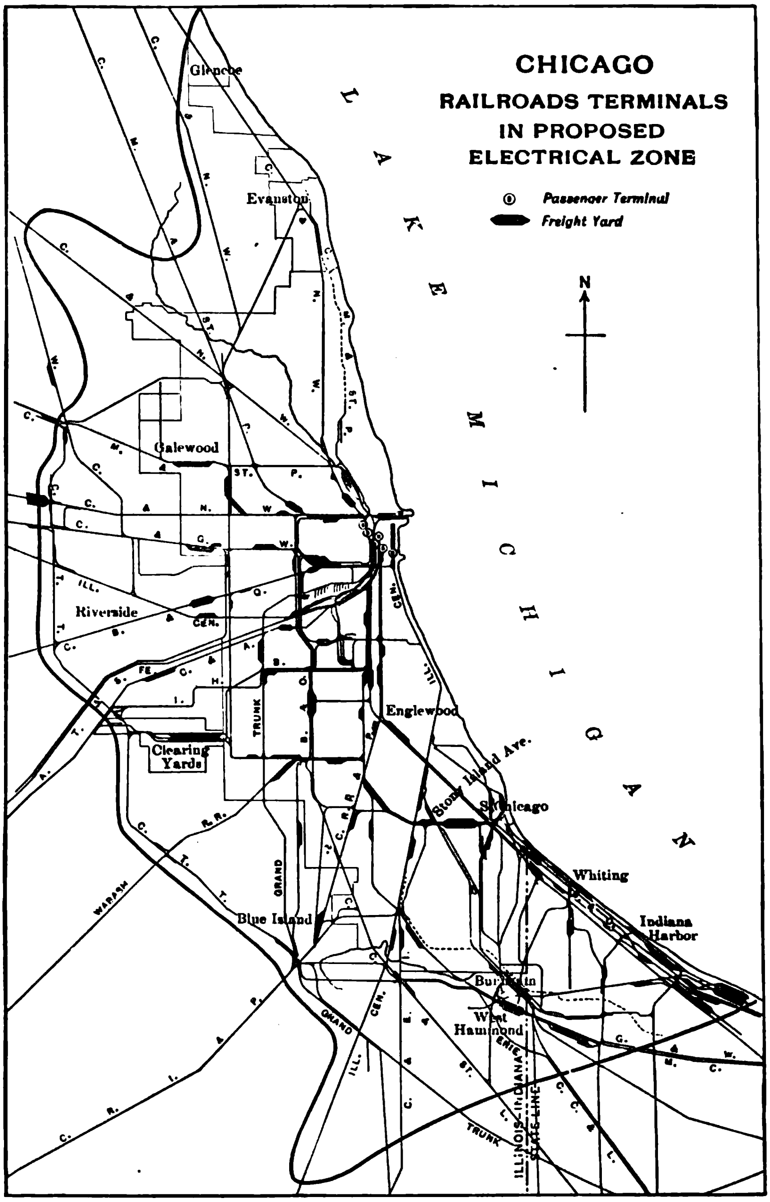
CHICAGO
RAILROADS TERMINALS
IN PROPOSED
ELECTRICAL ZONE
Passenger Terminal
Freight Yard
N
LAKE MICHIGAN
Glencoe
Evanston
Galewood
Riverside
Clearing Yards
TRUNK
Englewood
Stony Island Ave.
So. Chicago
Whiting
Indiana Harbor
GRAND
Blue Island
Burnham
West Hammond
WABASH
ILL. CEN.
ILLINOIS INDIANA STATE LINE
ERIE
TRUNK
GRAND

Fig. 17

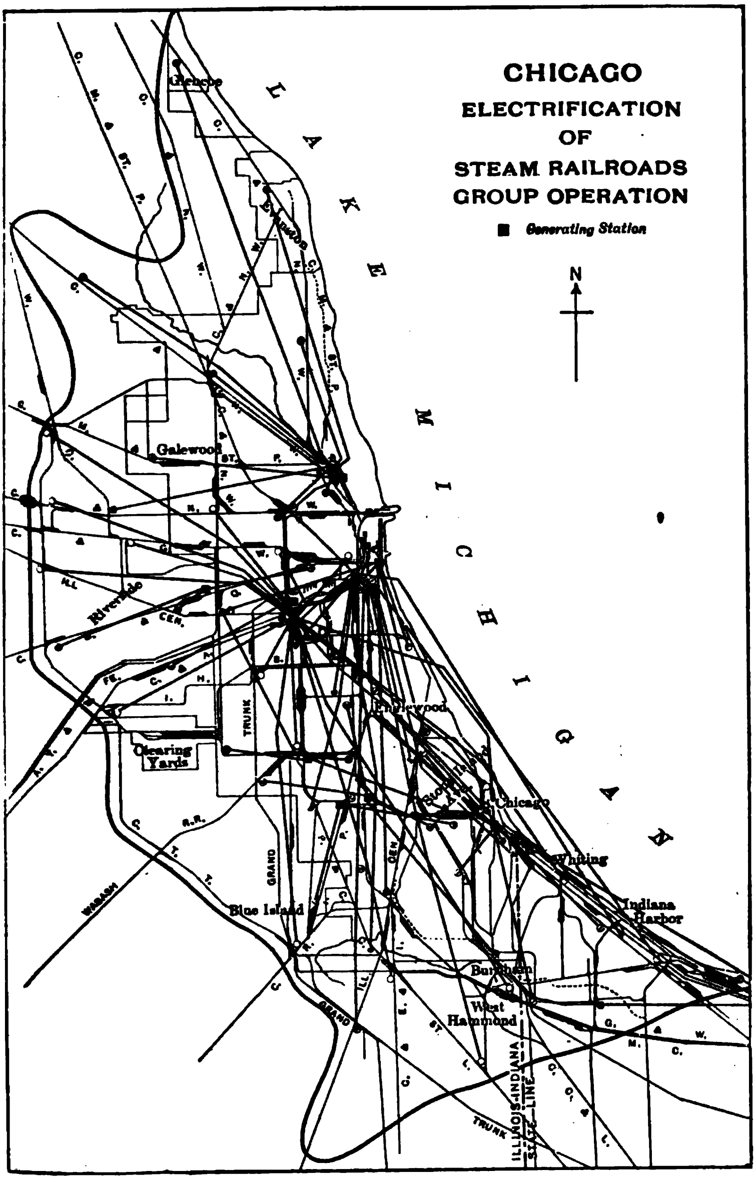
CHICAGO
ELECTRIFICATION
OF
STEAM RAILROADS
GROUP OPERATION
■ Generating Station
N
LAKE MICHIGAN
Glencoe
Evanston
Galewood
Riverside
Clearing Yards
TRUNK
GRAND
CEN.
ILL.
Englewood
Stony Island
South Chicago
Whiting
Indiana Harbor
Blue Island
Burnham
West Hammond
WABASH
GRAND TRUNK
ILLINOIS-INDIANA STATE LINE
C. & W. I.
C. M. & ST. P.
C. & N. W.
G. & W.
M. C.
C. C. & L.
E. & I.
C. T. T. R.R.

FIG. 18

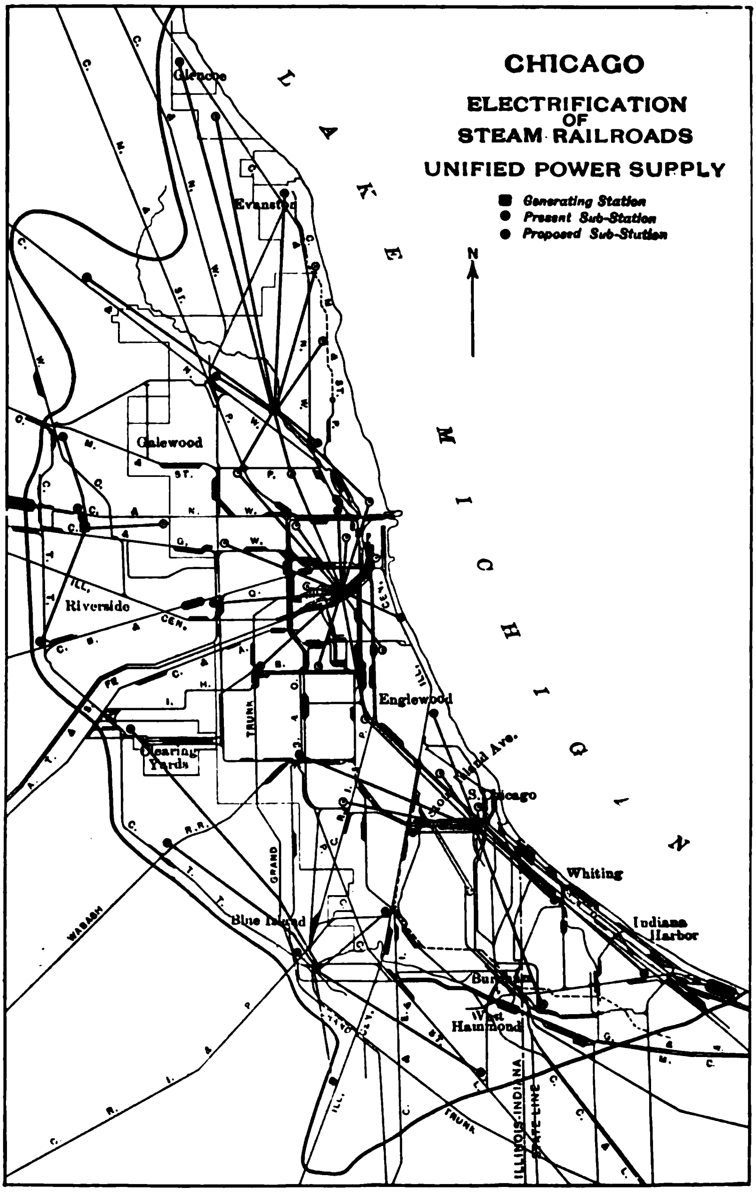
CHICAGO
ELECTRIFICATION OF STEAM RAILROADS
UNIFIED POWER SUPPLY
■ Generating Station
● Present Sub-Station
● Proposed Sub-Station
N
LAKE MICHIGAN
Glencoe
Evanston
Galewood
Riverside
Clearing Yards
Englewood
Stony Island Ave.
S. Chicago
Whiting
Indiana Harbor
Blue Island
Burnham
West Hammond
WABASH
GRAND TRUNK
ILLINOIS-INDIANA STATE LINE

Fig 19

one source, and shows the difference between purchased power and individual production.

Fig. 20 is the load diagram of the freight electrical requirements of the steam railroads in Chicago. This is a curve we have had worked out in relation to freight business, and it shows some rather interesting things. This freight curve has an extremely good load factor, estimated at 70 per cent daily and 60 per cent yearly. Through freights come in during the early morning hours and are broken up, switched and transferred from 7 o'clock in the morning on, and then during the late afternoon there is another switching and transfer peak caused by the making up of the through freights and getting them ready to go out as soon as the late afternoon passenger peak is over. The peak on the in and out freight of the day occurs from 7 o'clock in the evening on, due to these outgoing through freights which were made up in the late afternoon.

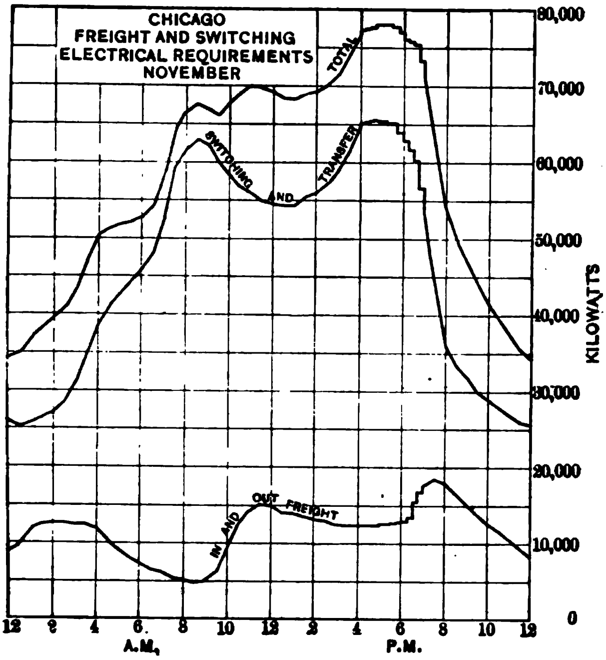

Fig. 20

Fig. 21 is the diagram of the freight earnings and monthly freight electrical requirements of the roads in Chicago. It shows the monthly gross freight earnings for two years for a group of Chicago roads, and also for the Elgin, Joliet & Eastern, which latter ought to show whether local Chicago conditions vary materially from the curve for the trunk lines included, as it has been impossible to get, in any way, the figures of local earnings of the different trunk railroads.

It has been assumed that normal electrical requirements of freight traffic will vary for the different months of the year similarly to the variation shown for the twelve roads for 1910 and 1911, and that these normal requirements will be increased during the winter months as shown, on account of increased traction or increased resistance due to the cold.

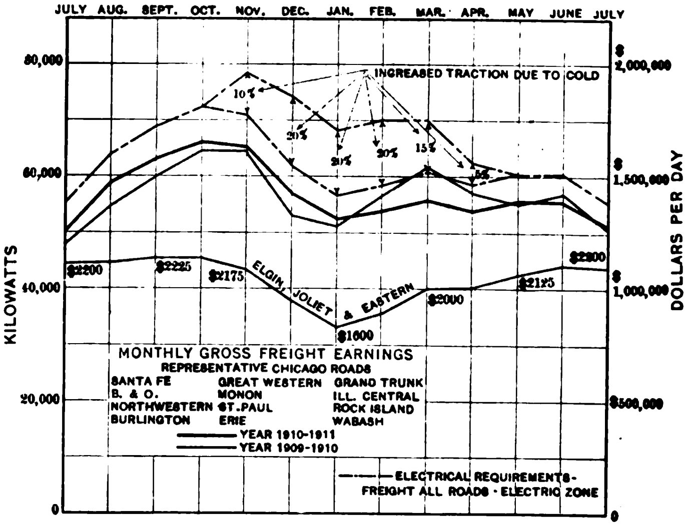

FIG. 21

Fig. 22 is the load diagram of the steam railroad passenger electrical requirements in Chicago. This diagram shows these requirements in December. It has the same general characteristics as the New York curve, with the high peak morning and evening, owing to the suburban passenger business and owing to the heating of the cars.

Fig. 23 shows the passenger earnings and monthly electrical requirements in Chicago, the latter being based on an assumed variation one-half that of the earnings for 1910–11. This diagram assumes, for through passenger business, that the cars

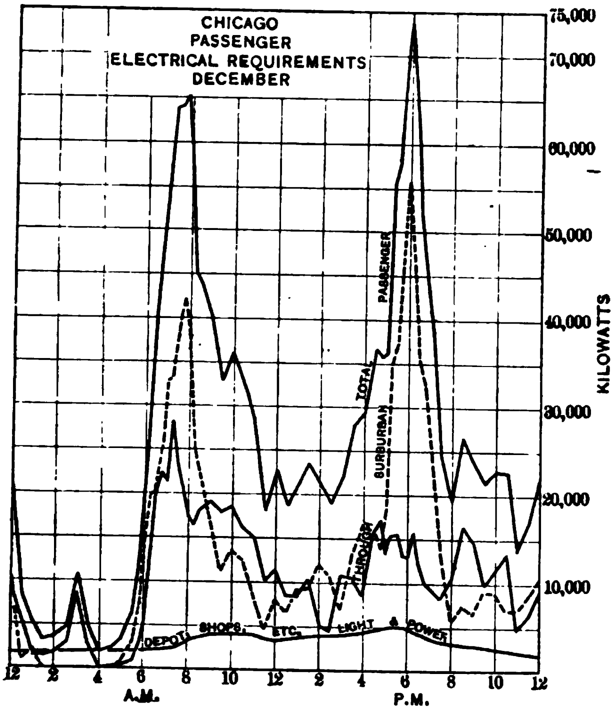
CHICAGO
PASSENGER
ELECTRICAL REQUIREMENTS
DECEMBER
75,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
KILOWATTS
TOTAL
PASSENGER
SUBURBAN
THROUGH
DEPOT, SHOPS, ETC., LIGHT & POWER
12
2
4
6
8
10
12
2
4
6
8
10
12
A.M.
P.M.

FIG. 22

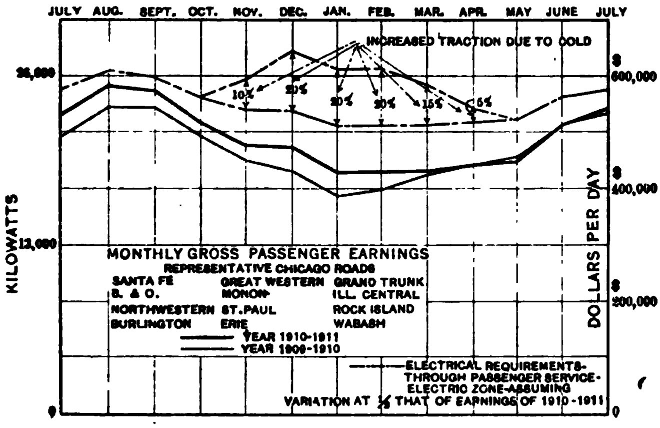
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
INCREASED TRACTION DUE TO COLD
10%
20%
20%
20%
15%
5%
26,000
13,000
0
KILOWATTS
$ 600,000
$ 400,000
$ 200,000
0
DOLLARS PER DAY
MONTHLY GROSS PASSENGER EARNINGS
REPRESENTATIVE CHICAGO ROADS
SANTA FE
B. & O.
NORTHWESTERN
BURLINGTON
GREAT WESTERN
MONON
ST.PAUL
ERIE
GRAND TRUNK
ILL. CENTRAL
ROCK ISLAND
WABASH
YEAR 1910-1911
YEAR 1909-1910
ELECTRICAL REQUIREMENTS-THROUGH PASSENGER SERVICE-ELECTRIC ZONE-ASSUMING VARIATION AT ½ THAT OF EARNINGS OF 1910-1911

FIG. 23

will be heated by steam, and you will notice the increased energy which is required for traction owing to the cold.

Fig. 24 shows the proposed steam railroad suburban electrical requirements, month by month, in Chicago. In addition to the

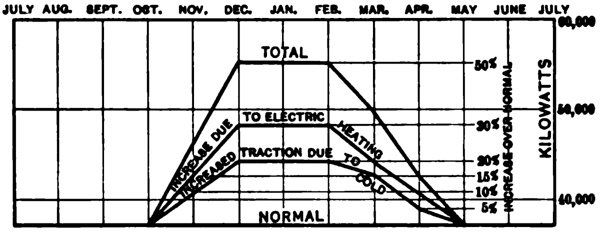

Fig. 24 — Electrical Requirements, Steam Railroad Suburban Service—Chicago Electric Zone

normal amount of energy required, there is the increased requirement for traction due to cold, and the increase due to electric heating.

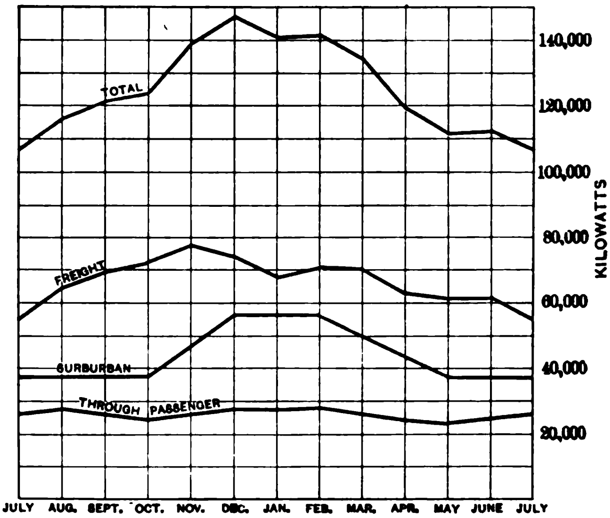

Fig. 25 — Monthly Variation in Maximum Electrical Requirements —Steam Railroads in Chicago Electric Zone

Fig. 25 shows the monthly variation in the total electrical requirements in the proposed electrification of the Chicago steam railroads. You will remember that the load factor of the through passenger business is extremely good, and of the freight business extremely good. That would indicate, except in the ten or twelve large cities to which I have referred, that the freight and passenger business ought to be very good throughout the country.

Fig. 26 gives a comparison between the swing maximum and the one-hour maximum load on the New York, New Haven and Hartford Railroad Company's Cos Cob station. This diagram of the New Haven road is important because it shows that small roads, installing their own plants, must provide a capacity sufficient to cover the maximum swing, which frequently lasts several minutes, and which, in the case of the New Haven road, apparently necessitates a reserve amounting to 74 per cent.

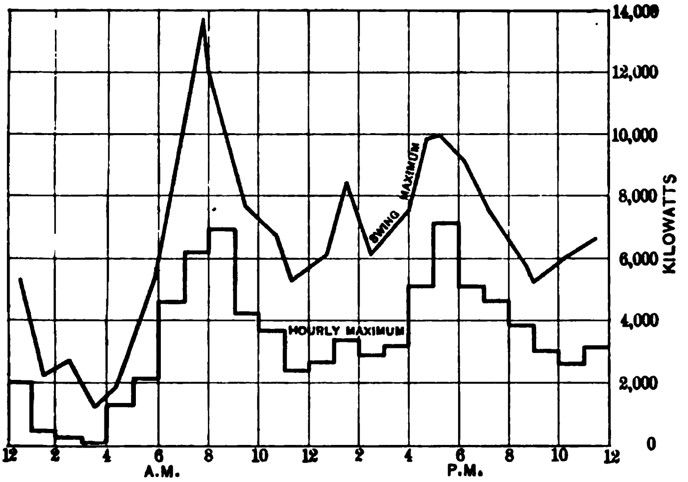

FIG. 26—DIAGRAM SHOWING RELATION OF SWING MAXIMUM TO ONE-HOUR MAXIMUM, N. Y., N. H. & H. R.R.—COS COB STATION, JULY 17, 1911

The three-phase capacity of their generators is 21,000 kw. and their maximum load is 9050 kw., which is a reserve of 132 per cent. But their single-phase operation really reduces the actual capacity of the generators, on a single-phase basis, to 15,000 kw., which is equivalent to 74 per cent reserve. They apparently have no greater reserve than is necessary, because they are installing three 6000-kw. three-phase units for additional capacity to take care of additional electrification. In another part of the paper, for the purpose of figuring the capacity of the steam plants if each of the roads installed its own plant, instead of using this actual 74 per cent reserve, we have assumed 50 per cent, to be conservative, as compared with 25 per cent reserve in case of purchase of energy.

The point brought out in this curve is also important from an operating standpoint, because, with a system of central stations for all energy used in a community, the entire load factor would be in the neighborhood of 60 per cent, as shown in Table I, compared with 25 per cent for this diagram using the maximum swing.

I would like to say just a little, before I conclude, with relation to the actual saving that, in my judgment, could be obtained, assuming that an effort were made to bring about the concentration of production and the concentration of primary distribution system in the area of greater Greater New York, that is, an area including the Jersey shore a little beyond the Hackensack river. The total saving in investment that could be worked out over a period of relatively few years, based on the experience that we have had in Chicago, would amount to about $18,000,000 to $20,000,000. That is in investment alone. The saving in operating expenses would amount to about $1,000,000 a year. Now, figuring fixed charges of 5 per cent for depreciation and 5 per cent for interest on the saving in investment, and adding to that the saving in operating expense, you have a sum almost equal to $3,000,000. That sum, capitalized at 5 per cent, means a creation of $60,000,000 of value.

At the rate of progress now going on in the neighborhood of New York the business is bound to double inside of ten years. If the present scheme is followed out,—if the traction companies have their own separate sources of supply, if the electric light and power companies have their own separate sources of supply, if the steam railroads that are apparently on the threshhold of electrification have their own sources of supply,—at the end of ten years, the waste in money which will have taken place, on a 5 per cent basis, will be somewhere between $140,000,000 and $175,000,000. The direct saving by a concentrated system of generation and primary distribution, leaving out of consideration altogether the saving in operating expenses, is of itself, in my opinion, sufficient to provide the necessary funds for that portion of steam railroad electrification centering in New York. That is, assuming the steam railroad requirements as about 170,000 kw., I do not believe that the portion of combined generating stations and combined primary distribution system for that purpose would cost much over $100 to $110 a kilowatt, taking it on the basis of a combined system.

The figures which my engineers have prepared indicate that if there should be made a systematic effort at massing production and massing primary distribution in the area referred to, the amount of property that would be realized or made available for increased business would be worth $18,000,000, or thereabout. I do not think that the power necessary for the steam railroads centering in New York, and the primary system necessary to take that current to the railroads, would cost over $18,000,000.

Now the savings are here at your feet. The engineering representatives of the interests that have these various public services in charge are most of them members of the Institute, and they can check up the figures. I will not attempt to burden the Institute records with the details, but they are at the disposal of anybody who wants to use them. I am speaking not from any theoretical point of view, but from my own knowledge and experience in developing the business which it is my pride to preside over;—I know that the change that I have been able to work there, from barely earning dividends to putting the property in a strong, conservative position, has been the result of following the policy that I have laid down here, and I urge the people who are interested to try to follow it out round New York. It is a policy that is worthy of the greatest engineers and worthy of the thought of the greatest financiers in this country. It is a conservation of the truest order. If the same policy is carried out throughout the United States, the conservation of fuel alone will be something tremendous. The conservation of labor will be something tremendous. The letting loose of capital that can be used in other directions will stimulate business.

There is no greater problem in the industrial world today, no problem that presents greater opportunities for the engineers to achieve distinction, no problem that presents greater opportunities for the financier to achieve distinction and profit, than the proper method of producing energy and distributing it in a given area, and involved in that question is the solution of providing money for that portion of the electrification of steam railroads that ends when the energy is put into the track.

Before concluding, I think it is but fair to my own staff that I should say that it would have been impossible for me to present this paper if it had not been for the loyal and valued assistance rendered me for three months in preparing data for this discussion, under the direction of Mr. Junkersfeld, of the

Commonwealth Edison Company, and the close personal work of Mr. Fowler, our chief statistician, Mr. Gear, our engineer of distribution, and Mr. Bird, one of the engineers of our contract department. These gentlemen whom I have mentioned have worked so hard on this matter, and given so much of their time to it, that it is only due to them that I should make this statement.

APPENDIX

ELECTRIC POWER REQUIREMENTS OF CHICAGO STEAM RAILROADS ELECTRIFIED—1911-1912

PREPARED BY PAUL BIRD, H. B. GEAR AND E. J. FOWLER

ELECTRICAL REQUIREMENTS OF FREIGHT SERVICE ON ELECTRIFIED STEAM RAILROADS IN CHICAGO DISTRICT—COMPUTATIONS MADE IN MARCH, 1912

The electrical requirements of the freight service of Chicago have been worked out for the same zone that is being considered by the Association of Commerce Committee on Smoke Abatement and Electrification of Railway Terminals.

The computations cover the year from July, 1911 to June, 1912, and it is assumed that the steam railroads in this district are electrified with no changes in the tracks and yards, and that freight is handled through the city in the same manner and following the same routes as it does today.

When the railroads are actually electrified there is no question but that great changes will be made in the freight terminals, and that a large part of the freight that now comes through the heart of the city will pass around and outside the city limits and possibly outside the electrified zone.

The results of the investigation are:

Month	Maximum demand	Kw-hr.	Load factor Per cent
July, 1911	55,200	28,814,400	70.3
August	63,800	33,303,600	69.6
September	68,700	34,624,800	70.3
October	72,100	37,636,200	70.2
November	78,000	39,312,000	70
December	74,200	38,732,400	70.3
January, 1912	68,200	35,600,400	70.3
February	70,200	32,853,600	69.7
March	70,000	36,540,000	70.3
April	62,500	31,500,000	70.1
May	60,400	31,528,800	70.2
June	60,300	30,391,000	70
		410,837,200	

The maximum demands and the consumption for December, the month during which the railway maximum demand would occur, are as follows:

DECEMBER FREIGHT REQUIREMENTS

Railroads	Maximum Demand	Kw-hr.
Wabash R.R.	1611	840,900
C. I. & L. R.R. (Monon)	736	384,200
L. S. & M. S. Ry.	3244	1,693,400
N. Y. C. & St. L. R.R. (Nickel plate)	1033	539,200
P. Ft. W. & C. Ry.	3352	1,749,700
B. & O. R.R.	1713	894,200
M. C. R.R.	2878	1,502,300
Erie R.R.	1680	877,000
P. C. C. & St. L. R.R.	2091	1,091,500
Chicago Great Western Ry.	1124	586,700
Northwestern Ry.	7605	3,969,800
Rock Island Ry.	2520	1,315,400
C. B. & Q. R.R.	5098	2,661,200
St. Paul R.R.	4127	2,154,300
Ills. Central R.R.	4377	2,284,800
Santa Fe R.R.	913	476,600
C. & A. Ry.	1572	820,600
C. & E. I. R.R.	3193	1,666,700
Grand Trunk R.R.	1201	626,900
Wisc. Central (M. S. P. & S. S. M.)	1256	655,600
C. & O. of Indiana	110	57,400
Chicago & Indiana Southern	148	77,300
Pere Marquette	368	192,100
Chicago & Western Indiana	967	504,800
B. & O.—C. T. R.R.	2390	1,247,600
C. Junction R.R.	4682	2,444,000
E. J. & E. Ry. (C. L. S. & E. R.R.)	3845	2,007,100
Belt Ry.	7071	3,691,100
Chicago, West Pullman & Southern Ry.	710	370,600
Ills. Northern	423	220,800
Manufacturers Junction	171	89,300
Misc. Belt Roads	1991	1,039,300
Total	74,200	38,732,400

Methods and Data Used in Making Computations. From the Association of Commerce Committee, a list was obtained of the number of steam locomotives used in the Chicago city limits in October, 1911. This list, showing the number of locomotives and locomotive hours in each class of service, was as follows:

Service	Number of locomotives	Working hours per day
Through freight	361	812
Switching	560	7223
Transfer	182	2378
Through passenger	336	801
Suburban passenger	200	1000

An estimate was made of the coal consumption per working hour of each class of freight locomotive, and from the coal burned in the city limits per day the necessary electrical requirements for the same service were computed.

OCTOBER, 1911—CITY LIMITS

	Through freight	Switching	Transfer	Total
Number of locomotives...........	361	560	182	1,103
" " working hours per day	812	7,223	2,378	10,413
*Lb. of coal per locomotive per hour	2,000	600	1,350	—
Tons of coal per day.............	812	2,196	1,602	4,610
Lb. of coal per hour.............	67,670	183,083	133,500	384,253
*Lb. of coal per hour per locomotive drawbar horse power.........	10	12	10	
*Efficiency (from drawbar to power house)................	60%	60%	60%	
Average electrical load in kw......	8,675	19,072	16,473	44,220
*Watt-hours per ton-mile..........	31	120	56	
Ton-miles per day...............	6,767,000	3,821,814	7,036,610	17,625,424

*Assumptions.

The pounds of coal per locomotive per working hour were assumed as shown above after consulting with several Chicago railway men. The tons of coal per day obtained in this way check very closely with similar figures published in the 1911 report of the Chicago Smoke Department, which figures were obtained directly from the railroad companies.

The pounds of coal per hour per drawbar horse power was assumed after discussing the subject with a prominent engineer of one of the large trunk line railroads. As a result of many actual tests he found that his road used about eight lb. of eastern coal per drawbar horse power. Correcting this figure for the difference in the heat value of the coal, the above figures were obtained for Chicago.

The efficiency of 60 per cent between the locomotive drawbar and the electrical power house was also chosen after discussing the matter with the same engineer. This takes into account the losses in the line, the transformers, and in the motors and gears of the electric locomotive.

The " watt-hour per ton-mile " figures are in accordance with results obtained on several electrified roads.

Having thus obtained the average power house load in kilowatts for the city limits and the month of October, 1911, the following steps were taken:

1. The average load of 44,220 kw. was apportioned among the various railroads operating in the city.

2. The results were increased, so as to apply to the Association of Commerce electric zone instead of the city limits.

3. A study was made of the movement of freight cars during the different hours of the day, and the different months of the year. The increased traction on account of cold weather was also considered. The daily, monthly and yearly load factors were thus obtained.

4. The maximum demand and consumption was then computed for each railroad and each month of the year.

5. The results were checked in various ways.

Apportionment of Total Average Load Among the Railroads. The total average load was found to be 44,220 kw. for October and within the city limits. This was divided among the different railroads in accordance with the coal consumed by their freight engines as given in the Smoke Department report of 1911.

Increase of Figures to Cover Assn. of Commerce Electric Zone. A statement of the track mileage of all railroads for the city limits and for the zone, was obtained from the Association of Commerce committee. With this as a basis, and from a careful study of the map, the figures of average electrical load were increased to cover everything within the zone. The average increase in load was 22 per cent.

The following table gives the average load in kw. for October, for the area within the city limits and also for the area within the electric zone.

Load Factors, etc. A daily load factor of 75 per cent was assumed for the entire freight business of the Chicago district. Mr. L. C. Fritch (now chief engineer of the Chicago & Great Western R.R.) investigated the subject of electrification of the Chicago terminal of the Illinois Central R. R. in 1909. He, of course, had access to all the records of the railroad and his load curves for the freight service show a load factor of 75 per cent. The subject of the movement of freight cars through Chicago was also discussed with several railway officials connected with roads which are among the largest handlers of freight in the city, and from the information thus obtained, it seems certain that this figure is about right.

Average load in kilowatts, October, 1911, 54,000.

Maximum kilowatts, October, 1911, 75 per cent load factor, 72,100.

FREIGHT SERVICE
AVERAGE LOAD IN KILOWATTS. OCTOBER, 1911

Railroad	City limits	Per cent increase	Electric zone	Maximum kilowatts 75 per cent load factor
Wabash R.R.	980	20	1180	1570
C. I. & L. R.R.	460	15	530	710
L. S. & M. S. Ry.	1890	25	2370	3150
N. Y. C. & St. L. R.R.	620	20	760	1010
P. Ft. W. & C. Ry.	1950	25	2430	3250
B. & O. R.R.	830	50	1240	1660
M. C. R.R.	1740	20	2080	2790
Erie R.R.	1020	20	1220	1630
P. C. C. & St. L. R.R.	1320	15	1520	2030
C. Great Western Ry.	750	10	820	1090
Northwestern Ry.	4430	25	5550	7400
Rock Island Ry.	1530	20	1840	2450
C. B. & Q. R.R	2970	25	3720	4950
St. Paul R.R.	2500	20	3000	4010
Ills. Central R.R.	2900	10	3180	4250
Santa Fe Ry.	580	15	670	890
C. & A. Ry.	1000	15	1150	1530
C. & E. I. R.R.	1940	20	2330	3100
Grand Trunk	700	25	870	1160
Wisc. Central	450	100	900	1200
C. & O. of Indiana	80	15	90	100
Chicago & Ind. Southern	100	15	110	140
Pere Marquette	230	15	260	350
Chi. & Western Ind.	640	10	700	930
B. & O.—C. T. R.R.	900	100	1800	2350
C. Junction	3400	0	3400	4550
E. J. & E. Ry.	1400	100	2800	3730
Belt Ry.	4900	5	5140	6870
Ch. W. Pullman & Southern	500	10	550	700
Ills. Northern	300	10	330	420
Mfg. Junction	100	25	120	160
Misc. Belt Roads	1100	25	1380	1940
Total	44,200		54,000	72,100

In order to get at the variation in the freight business throughout the year, the freight earnings of several of the principal railroads were plotted as shown in Fig. 21. The ratios obtained in this manner were used in getting the maximum kilowatts for each month of the year.

It was then decided to add to the maximum kilowatts of the winter months, the following percentages to take care of increased traction due to cold:

Month	Per cent added on account of cold
November	10
December	20
January	20
February	20
March	15
April	5

In getting at the monthly kw-hr., the Sunday requirements were assumed to be one-half of week-day requirements and four Sundays were used per month.

The following table shows the maximum kw., the kw-hr., and load factors for each month in the year.

FREIGHT ELECTRICAL REQUIREMENTS—CHICAGO

	Per cent of average daily earnings for October	Maximum kilowatts				Kw-hr.	Load factors
		Normal requirements	Additional on account of cold		Total maximum		
			Per cent	Amount			per cent
July, 1911....	76.5	55,200	—	—	55,200	28,814,400	70.3
August.......	88.5	63,800	—	—	63,800	33,303,600	69.6
September....	95.3	68,700	—	—	68,700	34,624,800	70.3
October......	100	72,100	—	—	72,100	37,636,200	70.2
November....	98.4	70,900	10	7,100	78,000	39,312,000	70
December.....	85.7	61,800	20	12,400	74,200	38,732,400	70.3
January, 1912.	78.9	56,800	20	11,400	68,200	35,600,400	70.3
February.....	81.1	58,500	20	11,700	70,200	32,853,600	69.7
March........	84.4	60,900	15	9,100	70,000	36,540,000	70.3
April.........	81.3	58,600	5	3,900	62,500	31,500,000	70.1
May.........	83.8	60,400	—	—	60,400	31,528,800	70.2
June.........	83.6	60,300	—	—	60,300	30,391,000	70
						410,837,200	

Average monthly load factor.....	70.1
Annual load factor..............	60.1

Normal maximum kilowatts assumed proportional to earnings.
Load factor for week day assumed at 75 per cent.
Sunday requirements ½ of week day, assuming four Sundays to month.

Ratio of Passenger to Freight Load:

Total kw.hr. per year, passenger...............183,452,500 — 31 per cent
" " " " " freight..................410,837,200 — 69 per cent
" " " " " passenger and freight....594,289,700 — 100 per cent

The 1911 report of the Chicago Smoke Department gives the average daily coal used by railway locomotives in city limits as follows:

Tons of coal per day, passenger.......................1163 — 21 per cent
" " " " " freight..........................4438 — 79 " "
" " " " " passenger and freight............5601 — 100 " "

This is a good check on the computations of the electrical energy required as to the proportion between passenger and freight service, for it is to be expected that locomotives engaged in freight service operate less efficiently than passenger locomotives.

Saving of Coal due to Electric Traction. The total electrical energy per year required by the electrified steam railroads of Chicago is:

Passenger service	183,452,500 kw-hr.
Freight	410,837,200 kw-hr.
Total	594,289,700 kw-hr.

At three lb. of coal per kw-hr. the total coal per year in the power houses would be 891,000 tons.

The 1911 report of the Chicago Smoke Department shows that the railroads burn in their steam locomotives about 1,850,000 tons of coal per year in the city limits. Increasing this figure by 22 per cent, it is seen that the railroads burn about 2,260,000 tons of coal per year in the electric zone. The ratio of the coal burned with electric operation to the coal burned with steam locomotives is 1 to 2.55.

Mr. W. S. Murray, electrical engineer of the New York, New Haven and Hartford R. R., in a paper presented at the 1911 convention of the A. I. E. E., said: "It has been demonstrated that the ratio between the coal burned for operating passenger trains by electric rather than by steam locomotives is 1 to 2. In the case of switching engines, this ratio is much greater, a figure of 1 to 3 being conservative."

Tonnage of Freight handled in Chicago. It is surprising to find how little information there is available on this subject. The railroads do not keep their records so that the tons or car loads of freight handled in the Chicago district may be obtained. Apparently the only record of any sort that was ever kept of the freight movements was in 1902 and 1903 when a committee of Chicago railway officials made a report on the interchange of freight between the different roads. This report was made with particular reference to the clearing yards of the Chicago Union Transfer Company. A copy of this report was borrowed from Mr. L. C. Fritch and by means of it an estimate was made of the tonnage handled by the 18 principal railroads operating in Chicago. The figures given in this report cover the number of loaded and empty cars handled during the year ending June 30, 1903. To get at the tons of freight handled in the year ending June 30, 1912, the following assumptions were made:

Weight of empty freight car	18 tons
" " loaded " "	40 "
Days per year	330 "
Increase of freight business from 1903 to 1912	67 per cent

The last figure was obtained by plotting a curve of the total ton-mileage of freight handled per year in the United States from 1902 to 1910. This information was obtained from Mr. Slasson Thompson's bureau of railway statistics. From the data given in the 1903 report it was also possible to approximate the number of switching movements, transfer movements and " in or out " or through freight movements.

After getting the number of tons of freight (including weights of cars) per day in each of these three classes of freight movement, by assuming the average distance travelled in each class of movement, the ton-miles were obtained. The mileages assumed were:

Through freight........................	7 miles
Switching............................	2 "
Transfer.............................	10 "

It may seem surprising that the average transfer haul is longer than the average in or out haul, but this is undoubtedly true. The list previously given shows 2378 transfer locomotive hours per day as against 812 through freight locomotive hours.

Knowing the average ton-miles per hour and applying figures for " watt-hours per ton-mile," the average electrical load was obtained. The table on the following page shows the results of these computations.

As this 1903 Interchange report only covered the 18 principal trunk line railroads, the figures thus obtained serve only to check a part of the results arrived at by the other methods.

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Report—February, 1911.

Report—" Assembling—Interchange, Chicago, Illinois," by Committee of Railway Officials, 1903.

FREIGHT ELECTRICAL REQUIREMENTS—18 TRUNK LINE RAILROADS

	Through freight Ave. length of movement—7 miles Watt-hours per ton-mile—30			Switching Ave. length of movement—2 miles Watt-hours per ton-mile—120			Transfer Ave. length of movement—10 miles Watt-hours per ton-mile—60			Total ton miles per day	Total average kw.
	Tons per day	Ton-miles per day	Kw. average	Tons per day	Ton-miles per day	Kw. average	Tons per day	Ton-miles per day	Kw. average		
Wabash R. R.	32,018	224,126	280	33,735	67,470	337	14,392	143,920	360	435,516	980
C. I. & L. R.R.	15,647	109,529	137	16,066	32,132	161	6,720	67,200	168	208,861	460
L. S. & M. S. Ry.	60,232	421,624	527	68,141	136,282	681	27,323	273,230	683	831,136	1890
N.Y.C. & St.L. R.R. ..	21,876	153,132	191	25,256	50,512	253	7,328	73,280	183	276,924	620
P. Ft. W. & C. Ry. ...	62,312	436,184	545	71,868	143,736	719	27,574	275,740	689	855,660	1950
P. C. C. & St. L. R.R. .	43,474	304,318	380	47,602	95,204	476	18,779	187,790	469	587,312	1320
B. & O. R. R.	23,990	167,930	210	27,425	54,850	274	13,915	139,150	348	361,930	830
M. C. R. R.	62,144	435,008	544	66,402	132,804	664	21,507	215,070	538	782,882	1740
Erie R. R.	30,369	212,583	266	36,819	73,638	368	15,393	153,930	385	440,151	1020
C. Gt. Western Ry. ...	23,769	166,383	208	24,910	49,820	249	11,540	115,400	288	331,603	750
Northwestern Ry.	122,091	854,637	1068	187,258	374,516	1873	59,602	596,020	1490	1,825,173	4430
Rock Island Ry.	50,007	350,049	437	64,853	129,706	648	17,797	177,970	445	657,725	1530
C. B. & Q. R. R.	83,010	581,070	726	136,838	273,676	1368	35,054	350,540	876	1,205,286	2970
St. Paul R. R.	90,580	634,060	792	108,788	217,576	1088	24,992	249,920	625	1,101,556	2500
Ill. Central R. R.	90,814	635,698	794	109,328	218,656	1093	40,459	404,590	1011	1,258,944	2900
Santa Fe Ry.	19,168	134,176	168	24,176	48,352	242	6,717	67,170	168	249,696	580
C. & A. Ry.	29,646	207,522	259	33,463	66,926	335	16,061	160,610	401	435,058	1000
C. & E. I. R. R.	61,460	430,220	538	62,779	125,558	628	30,898	308,980	772	864,758	1940
Total	922,607	6,458,249	8070	1,145,707	2,291,414	11,457	396,051	3,960,510	9899	12,710,173	29,400

DETERMINATION OF ELECTRIC POWER REQUIRED TO OPERATE PASSENGER TRAINS AT CHICAGO TERMINALS

General Plan. Observations were made on a mid-week day between 4 and 5 p.m. as to the number and kind of cars making up each train entering and leaving each of the six passenger stations now in operation.

At the Northwestern station and the Grand Central station these observations were extended to include all trains entering and leaving the station throughout a 24-hour period, these two being chosen as the ones representing the heaviest and lightest traffic, respectively.

From the data secured by observations, average weights of trains for the different classes of service were derived and from these weights and the special time schedules gotten out by the railroads for the use of their employees, the running time and average kilowatt demand for each train were calculated for all through trains for the entire 24 hours. Twenty-four-hour load curves were plotted from average weights of trains for the suburban service of the Northwestern and LaSalle stations, these stations being taken as typical of the suburban service of other stations.

Through trains were considered as being operated by locomotives, and suburban trains as being made up of multiple-unit cars similar to those used by the New York Central, with two trailers to three motor cars. From these train diagrams, load curves were derived for the rush hours from 4 to 8 for the six terminal stations, the curve for through trains being determined separately from that of the suburban trains.

From the observations taken in the other stations between 4 and 8 p.m. suburban load curves were plotted for those hours and a total curve for suburban trains made up for the hours of 4 to 8 p.m., thus fixing the maximum for the suburban service at all stations.

Having determined the ratio of the combined suburban curve of the Northwestern and LaSalle stations to the total suburban curve for the hours of 4 to 8 p.m., this ratio was applied to the Northwestern and LaSalle stations' suburban curve for the remainder of the 24 hours in order to get the total suburban load curve.

Twenty per cent was added to the through train load to allow for increased traction due to cold weather and 50 per cent to suburban train load for increased traction and electric light and heating. From these increased values the load curve for the winter months was made up.

The schedule of percentages of increase added during the fall and spring months for increased traction and heating which was used in connection with the freight power data, was applied to the passenger load curve for the purpose of determining the kilowatt-hour consumption for the different months of the year and the annual kilowatt-hour consumption.

Train Weights. The weights of trains were calculated on the following basis:

Locomotives	110	tons
Baggage, express and combination cars	60	"
Day coaches	40	"
Ordinary pullmans	62½	"
Steel pullmans	75	"
Diners	56	"
Trailer cars (suburban)	40	"

Method of Calculation. From the total weight of the train and the distance travelled in the zone the ton-miles were derived. For locomotive trains an energy consumption of 40 watt-hours per ton-mile was assumed; for the express run of suburban trains, 55 watt-hours per ton mile; and for the local run of express and local trains where stops are frequent, 120 watt-hours per ton-mile. From the kilowatt-hours used by the train and the elapsed time as figured from the time schedules, the average kilowatts required by the train during the time of its run was calculated.

From the kilowatt demand of the trains the load curve was made up by the use of a train diagram showing the number of trains and the power taken by them at each half-hour interval, except during the peak hours, when the calculations were made for each 15 minutes.

Fig. 23 shows how the through passenger load would vary throughout the year, making proper allowances for increased traction due to cold weather, also taking into account the variation in the amount of business done. It is assumed that the amount of energy required for the different months, exclusive of traction due to cold, would differ from January by a percentage equal to one-half the per cent difference between the earnings for January and the other months of the year.

Fig. 24 shows the suburban requirements of the year; the normal requirements are assumed as constant and the additional due to increased traction and heat are shown.

TOTAL LOAD CHICAGO THROUGH TRAINS

Time	Grand Central	North-western	LaSalle	Union	Dearborn	I.C.	Total kw.
A.M. 12:00	—	—	1600	1470	2090	1340	6,500
12:30	360	—	610	1470	340	1180	3,960
1:00	360	—	610	—	—	—	970
1:30	—	—	250	730	—	—	980
2:00	—	—	1180	—	—	—	1,180
2:30	—	—	1190	—	720	—	1,910
3:00	—	620	1400	1900	590	1490	6,000
3:30	—	—	—	580	—	1360	1,940
4:00	—	—	—	—	—	—	—
4:30	—	140	—	—	—	—	140
5:00	—	140	160	—	—	—	300
5:30	—	—	—	—	—	550	550
6:00	560	—	1750	990	—	550	3,850
6:30	560	1180	3940	4220	2860	1570	14,330
7:00	280	1760	3540	4380	2640	2710	15,310
7:30	530	2400	4650	3880	2710	2370	16,540
8:00	1270	1990	3280	3990	940	940	12,410
8:30	1130	3350	4450	2390	810	940	13,070
9:00	1140	3060	3100	3000	3100	390	13,790
9:30	—	2750	2620	3330	3300	1680	13,680
10:00	370	2810	1830	4220	750	3280	13,260
10:30	370	1320	3830	2410	1090	2590	11,610
11:00	—	3750	3170	1600	1270	1050	10,840
11:30	—	1050	1600	2200	1810	540	7,200
P.M. 12:00	310	1050	2280	2060	1950	580	8,230
12:30	580	720	1510	—	2710	570	6,090
1:00	960	560	1930	700	650	1280	6,080
1:30	—	2080	1940	1730	540	1200	7,490
2:00	—	200	1160	1900	540	—	3,800
2:30	—	850	2420	—	—	—	3,270
3:00	470	1250	1580	1670	1700	1120	7,790
3:30	—	1650	3000	1380	980	560	7,570
4:00	890	930	1240	1880	590	450	5,980
4:30	890	1890	2630	2520	1550	2070	11,550
5:00	730	750	3280	2230	1580	930	9,500
5:30	270	1040	4190	3530	1160	930	11,120
6:00	440	750	2530	2730	1300	1530	9,280
6:30	930	3080	630	2490	—	1530	8,660
7:00	320	2240	1340	—	920	1780	6,600
7:30	—	460	1300	1560	590	1860	5,770
8:00	—	1010	1660	2350	720	1820	7,560
8:30	—	3000	2510	3160	1370	1810	11,850
9:00	—	1480	3010	1480	2900	1710	10,580
9:30	840	—	1860	590	2080	1630	7,000
10:00	870	610	940	2950	1140	1660	8,170
10:30	870	1800	1990	3410	870	580	9,520
11:00	—	1200	980	590	510	—	3,280
11:30	430	—	2310	—	1710	—	4,450
12:00	—	—	1600	1470	2090	1340	6,500

The above figures do not include the allowance for increased traction during winter months.

SUMMARY, ELECTRICAL REQUIREMENTS FOR PASSENGER SERVICE

Normal Requirements. The suburban service is assumed the same as January throughout the year. Sundays, for the suburban service, are assumed 33⅓ per cent of a week-day.

REQUIREMENTS OVER NORMAL

	Suburban and through. Increased traction on account of cold	Surburban only. Heat
November..................	10 per cent	15 per cent
December..................	20 " "	30 " "
January....................	20 " "	30 " "
February..................	20 " "	30 " "
March......................	15 " "	20 " "
April........................	5 " "	10 " "

	Daily earnings over January expressed in per cent	Coincident maximum kilowatts			
		Through	Suburban	Light and power for depots, offices shops, etc.	Grand total
July, 1911....	12.6	11,490	37,310	3550	52,350
August.......	18.8	12,120	37,310	3550	52,980
September....	17.6	12,000	37,310	4000	53,310
October......	10.4	11,260	37,310	4250	52,820
November....	5.9	11,880	46,640	4570	63,090
December.....	5.7	12,940	55,960	4850	73,750
January, 1912.	—	12,240	55,960	4850	73,750
February.....	0.2	12,260	55,960	4570	72,790
March........	0.3	11,760	50,370	4250	66,380
April.........	1.7	10,890	42,910	4000	57,800
May.........	2.6	10,470	37,310	3550	51,330
June.........	10.3	11,250	37,310	3550	52,110

	Kilowatt-hours				Load factor
	Through	Suburban	Light and power per month	Grand	
July, 1911	6,633,600	5,679,200	1,850,200	14,163,000	36.4%
August.......	7,045,700	5,816,700	1,882,700	14,745,100	37.4%
September....	6,743,500	5,611,400	1,836,500	14,191,400	36.9%
October.......	6,504,000	5,679,200	1,895,000	14,078,200	35.8%
November....	6,680,000	7,014,300	1,895,000	15,589,300	34.3%
December...	7,472,500	8,518,800	2,068,000	18,059,300	32.8%
January, 1912	7,116,800	8,725,100	2,104,200	17,946,100	32.9%
February.....	6,658,700	8,109,200	1,816,600	16,584,500	32.7%
March.......	6,795,500	7,666,900	1,895,000	16,357,400	33.1%
April..........	6,123,400	6,453,100	1,836,500	14,413,000	34.6%
May.........	6,085,000	5,816,700	1,882,700	13,784,400	36 %
June.........	6,281,700	5,473,800	1,785,300	13,540,800	36.1%
Total...	80,140,400	80,564,400	22,747,700	183,452,500	28.3%

Through-train requirements for different months were obtained by increasing the January figures by one-half the excess of the daily passenger earnings of those months. Sunday, for through-trains, is taken as 80 per cent of a week-day.

The energy required for light and power for depots, offices, shops, etc., battery charging, and operating switches, is assumed at 5000 kw. maximum and 50 per cent annual load factor.

CALCULATION OF TRANSMISSION AND CONVERSION SYSTEM FOR PASSENGER AND FREIGHT LOADS

To determine the location and size of substations required for the supply of the third rail system, the positions of all passenger trains which will be operating in the electric zone at 6:05 p.m., the time of the evening peak, were indicated upon a railroad map of Chicago, these positions being determined from the train schedules. No train schedules were available for freight trains and it was therefore necessary to locate these on the map in amounts approximately equal to the demand of a single train, chiefly near the freight yards where switching is the heaviest, a few trains being located along the main line.

Two general plans of power supply were assumed: (a) based on the installation of a separate power system for each road or group of roads using the same tracks or operating under allied financial interests, and (b) based upon the entire power supply being operated as a unified system, the energy being derived from the nearest station of the Commonwealth Edison Company or the Public Service Company, and all stations being used to supply all the roads which came within an economical radius thereof.

The position of substations was then fixed by allowing a distance of four to five miles apart on the larger roads and six miles apart on the smaller ones.

In scheme (a) where operation is contemplated by groups, power houses were located at points where condensing water was available, where it was possible to secure such sites within a reasonable distance of the railroad company's tracks.

However, in the smaller system where the loads were from 5000 to 10,000 kw. this was not entirely feasible and sites were selected in some cases with reference to the distribution of the load.

In selecting the capacity for generating stations under group operation, it was considered that from 50 per cent to 75 per cent surplus capacity would be required to take care of swings in the load and provide suitable reserve.

Fig. 26 shows swings of nearly 100 per cent over one hour maximum for the New York, New Haven & Hartford Cos Cob station.

Transmission lines were laid out on a basis of a line for each 3000 kw. of load with a reserve line for each substation. The reserve supply was secured in the smaller substations by using one line with taps to two or three substations.

In the plan for unified power supply it was assumed that the present 600-volt substations of the surface and elevated roads would be available, when increased in capacity, as sources of 600-volt supply for all roads coming within an economical range of their distribution, and the necessary number of additional lines to these substations to supply the steam railroad load are included in the estimates.

It is assumed that transmission lines would be run overhead along the railroad company's right-of-way in the outlying portions of the city where steel pole construction of a substantial character could be employed. Wherever lines were run on public streets it was assumed that they would be carried underground.

Summary of Results

Under a unified plan of power supply, only 21 additional substations would have to be established and the total number would be only 43 as compared with 72 substations under group operation.

The number of transmission lines under the unified plan would be 81 as compared with 132 under group operation, and there would be over 2½ times the length of line required for group operation as compared with the unified plan.

The data for the unified plan are as follows:

Number of substations	43
Number of lines	81
Capacity of substations, kw	205,000
Capacity of generating stations, kw	142,000
Length of lines, feet	1,390,000

The data for group operation appear in the following table.

A comparison of the investment necessary for unified power supply, as compared with a separate supply for each road or group of roads, shows the following saving in favor of unified power supply:

Power-house capacity	99,500 kw.
Substation capacity	39,500 kw.
Transmission line cables in feet	2,273,000 feet

Railroads	Kilowatts			Capacity in kilowatts		No. of substations	No. of lines	Length of lines
	Freight load	Pass. load	Total load	Generating stations	Substations			
1. Ill. Cent.								
M. C. Pass.	4,600	20,400	25,000	37,500	37,000	7	19	329,000 ft.
2. L. S. & M. S.								
M. C. R. R. Freight.								
C. R. I. & P. Pass.	8,750	7,750	16,500	24,000	28,000	7	14	255,000 ft.
3. C. & N. W.	8,000	25,000	33,000	50,000	51,000	8	19	479,000 ft.
4. C. M. & St. P.	4,350	3,050	7,400	14,000	14,000	4	8	121,000 ft.
5. C. & Gt. W.								
Grand Trunk.								
B. & O. C. T.								
I. H. Belt	10,500	2,000	12,500	22,500	36,500	15	21	1,224,000 ft.
6. P. F. & W. & C.								
P. C. C. & St. L.	5,700	2,000	7,700	14,000	20,000	10	12	637,000 ft.
7. Erie.								
C. I. & L.								
C. & W. I.								
Wabash.								
Belt	16,300	3,200	19,500	30,000	32,000	10	18	290,000 ft.
8. Santa Fe.								
Alton	2,600	2,000	4,600	9,000	6,000	2	4	29,000 ft.
9. C. B. & Q.	5,400	5,400	10,800	16,500	14,000	3	8	47,000 ft.
10. C. R. I. & P.	2,400	3,000	5,400	9,000	9,000	3	6	15,000 ft.
11. Chicago Junction	5,000	—	5,000	9,000	—	—	—	—
12. E. J. & E.	4,100	—	4,100	6,000	7,000	3	3	237,000 ft.
Total	77,700	73,800	151,500	241,500	244,500	72	132	3,663,000 ft.

In addition to the above saving, there is a corresponding saving in conduit construction, where the lines are underground, and in pole line construction, where the lines are overhead.

There is also a corresponding and possibly even greater saving in the 600-volt feeder, cable and conduit or pole lines for same.

It must also be borne in mind that, where the stations and substations are of larger average capacity, the investment per kilowatt is less than where the same load is distributed over a larger number of stations and substations. This same principle applies to transmission and distribution cable and conduit, and pole lines.

Also the same principle applies, to fully as great an extent, to the operating and maintenance cost of stations, substations and lines.

SUMMARY
TOTAL ELECTRICAL REQUIREMENTS—ALL STEAM ROADS

	Load at time of monthly maximum demand		
	Freight	Passenger	Total
July, 1911	54,250	52,350	106,600
August	62,700	52,980	115,680
September	67,500	53,310	120,810
October	70,900	52,820	123,720
November	76,700	63,090	139,790
December	73,000	73,750	146,750
January, 1912	67,000	73,020	140,020
February	69,000	72,790	141,790
March	68,800	66,380	135,180
April	61,400	57,800	119,200
May	59,400	51,330	110,730
June	59,300	52,110	111,410

	Kilowatt-hours			
	Freight	Passenger	Total	Load factor
July, 1911	28,814,400	14,163,000	42,977,400	54.3%
August	33,303,600	14,745,100	48,048,700	55.8%
September	34,624,800	14,191,400	48,816,200	56.2%
October	37,636,200	14,078,200	51,714,400	56.4%
November	39,312,000	15,589,300	54,901,300	54.7%
December	38,732,400	18,059,300	56,791,700	52 %
January, 1912	35,600,400	17,946,100	53,546,500	51.5%
February	32,853,600	16,584,500	49,438,100	51.8%
March	36,540,000	16,357,400	52,897,400	52.5%
April	31,500,000	14,413,000	45,913,000	53.4%
May	31,528,800	13,784,400	45,313,200	55 %
June	30,391,000	13,540,800	43,931,800	55 %
Total	410,837,200	183,452,500	594,289,700	46.2 %

DISCUSSION ON "THE RELATION OF CENTRAL STATION GENERATION TO RAILWAY ELECTRIFICATION" (INSULL), NEW YORK, APRIL 5, 1912, AND BOSTON, MASS., JUNE 26 AND 27, 1912.

DISCUSSION AT NEW YORK, APRIL 5, 1912.

John W. Lieb, Jr.: The Institute owes a debt of gratitude to our distinguished fellow member from Chicago, who has presented such a vast and important economic proposition so lucidly and convincingly, and who has come before us and with such frankness and without reserve, has given us the benefit of the experience of his company, and of the advantages which have accrued to it from his far-sighted and economical administration

The address that we have listened to is of great advantage to us, and I think we may say, with some regret, that we are not often favored with such addresses before this body. Our problems, as they have been discussed here, have unfortunately been limited to problems of systems, and we have had here time and again, as you all know, pretty active discussions as to choice of systems. May it not be that we have wasted a large amount of energy and time on some of the details of the problem, of its minor construction features, and have let slip by some of the more economic and fundamental propositions? I think, therefore, that the Institute is fortunate in having had presented an address which opens before us some of the larger aspects of the engineering problems with which we are face to face.

Not having had these figures in hand before, which Mr. Insull now presents to us, I am unable to discuss them from the standpoint of detail application, and I shall therefore approach the subject from a rather general standpoint. The first thing that strikes one is the large economical advantage which all of the central stations referred to, speaking solely from the light and power generating standpoint, have achieved in attaining the rather significant load factors that are here indicated. These may with advantage to us be compared with corresponding load factors which obtain in the lighting and power stations abroad, which have not yet entered the railway field. It will be seen that the lighting and power stations here have reached a favorable economic position as regards high load factors, and advantageous investment costs, which has been due to their stimulation within the light and power field of all possible uses of electricity. It is undoubtedly due to their energetic endeavors to cultivate the field that they have been able to reach the high load factors here indicated, also taking advantages of the diversity factor resulting from the different applications of their product.

Mr. Insull, in his work in Chicago, has demonstrated in a striking manner the advantages of also invading the railroad field, and securing the benefits of that further diversity factor which results from a combination of the railway load and the lighting load. It seems to me that one of the significant features of these diagrams is the great advantage, rather difficult to estimate, which accrues from the fact that the lighting load, particularly in the morning hours, leaves the light and power stations with a very large element of spare capacity at a time when the railroads, and particularly the surface roads, have, or are likely to have, an excessive demand. This feature is rather strikingly indicated in the diagram.

I wish to point out another thing in relation to this subject, and that is the question of the systems. If we are in the future to obtain the economic advantages of consolidation of systems, the economical combining of these systems will be greatly facilitated if they are operated by a similar type of current. If we are to combine these systems and have 15 cycles for part of the railroad load, 25 cycles for another part of the railroad load and part of the lighting load, and then 60 cycles for another part of the lighting load, the problem will be very difficult of solution. The figures which Mr. Insull has given us as to the economic possibilities of the situation have a very important bearing on this debated question of systems.

Dugald C. Jackson: I desire to express very briefly my appreciation of the creative imagination of Mr. Insull. When I say creative imagination, I mean an imagination which conceives and puts into useful effect those things which are of advantage to the engineering and the commercial and the social world. I think it is not too much to say that Mr. Insull's work in the lines that he has presented in this paper has been of much moment to electrical engineering, and is now proving of moment, and will prove of greater moment, to the general social fabric.

The question of obtaining power conveniently delivered for any purpose, whether for locomotion, for lighting, for heating, for cooking, for mechanical power used in the shop—it makes no difference what the use is—this question of the delivery of power where it may be utilized conveniently and for the least cost is one of the most important matters before our modern civilization, where we have our peoples closely contracted within narrow limits in the cities, and it is only by working out the problem in the broad-minded and comprehensive fashion that has been presented in this paper that we can make the cities, as they are growing to be, inhabitable places. This is one of the things that our economists have not yet thoroughly grasped. The practise of the engineers has outrun the theories of the economists. The economists have not been able to keep pace, and we are constantly, as a consequence of that situation, having contests between the engineering world and the general world of economics; but it seems to me that presentations of this kind before engineering societies must be an aid toward bringing the economic views and the engineering views into harmony. The economists are trying to get at the truth and the engineers are working for the purpose of producing truths, and consequently they must ultimately get together.

Charles P. Steinmetz: The data given in the paper are complete and conclusive facts, derived from actual operating experience, and as such must stand unchallenged.

I wish to say that this paper from Mr. Insull is the most important paper read before the Institute to which I have listened for years, in that it announces the approach of a new era in the electrical industry, the change from the diversified electric generating systems or diversified classes of work, to electricity as the universal source of power serving the community, the territory, the state, and nation. The great and important feature of the paper is that these curves and data are not the conclusions of an enthusiastic engineer who tells us what can be done, but are an enunciation of the principles which Mr. Insull has carried out in making this system the greatest and most successful central station of the world.

Lewis B. Stillwell: I cannot claim to hold a brief for the railroads, primarily, my first experience having been more especially in the general field of power transmission and in the theoretical contemplation of these possibilities which Mr. Insull in Chicago has worked out into actual demonstration. I regard the paper as peculiarly important, for the reason that Mr. Insull is the one man who has had the courage to translate into action what others have realized in theory, somewhat less clearly than he, for many years.

It might be inferred from what has been said that there is another side to this proposition of indefinite and general aggregation of plants, and like every other question of engineering, there is another side of it. You will note, if you will examine these curves, that the advantages that accrue from the utilization of the diversity factor decrease rather rapidly as the size of the individual aggregated plants increases. It is a very different proposition when you come to put together two 100,000-kw. plants from what you have when you are dealing with a proposition which involves six-light and ten-light customers—you are running toward one of the limitations. One practical limit interposes itself in respect to continuity of service; another that we encounter is imposed by the diversity of voltage. Unfortunately, it is complicated very greatly in many cases by the fact that we have several frequencies in commercial use.

I should like to ask Mr. Insull a question which may bring out a useful answer. I understand that he contemplates the possibility of extending his operations to the northern half of the state of Illinois. In many of the towns of that state he will find 60-cycle apparatus used for lighting, and I would ask Mr. Insull whether in undertaking to light a town at a distance of 50 miles from Chicago, he would propose to do this directly from his transmission circuit, or whether he would regard it as necessary either to employ storage batteries or carry turbo-alternators or some other device floating on the line to overcome the difficulty which results from momentary interruption of service?

It is not so very many years since the Manhattan Railway Company bought the 5000-kw. units now operating in the 74th Street station, and it is only seven years since the Interborough Company bought a number of additional similar units now operating at 59th Street. These units need not be apologized for. They are operating today and have been operating since they started, practically without interruption. At the time they were purchased they were, in my judgment, the only wise thing to install. But at present turbo-alternators of the latest design have a steam economy better by 4 lb. per kw-hr. than that of the 5000-kw. engine-driven machines under conditions of constant load. Taking Mr. Insull's figures for Boston, New York and Chicago, I estimate that difference represents something over one million tons of coal per annum; in other words, the progress of the art within these comparatively few years, not more, say, than eight years, is such that the improvement in the prime mover has resulted in an economy in coal, alone, amounting to 30 per cent of the present coal consumption.

This is a factor which powerfully assists us in carrying out centralization. It offers another very good reason why we can afford, to a certain extent, and more rapidly as the years go by, to set aside the older apparatus in favor of newer and larger units and consolidation of these units.

Benjamin F. Wood: Mr. Insull has indicted the railroad men for not purchasing power. I am one of those railroad men. The Pennsylvania Railroad has here in New York and in operation a power station representing an expenditure of about $4,000,000. The total electrical work, exclusive of locomotives, represented an expenditure of about $8,000,000. If we could have purchased that power we would have saved investment of that $4,000,000, and if it could have been purchased at a rate the same as it is being sold in Chicago, we could have paid a dividend on the other $4,000,000 of about 6 per cent. We are not the guilty party.

Cary T. Hutchinson: In spite of the interesting curves which the author has shown us and his claim of greatly reduced cost of energy supply when concentrated, on account of the so-called " diversity " factor, another aspect of the question obtrudes itself; that is, the cost of energy to the ultimate consumer. Great central stations may be able to supply more cheaply than smaller ones, but the final question is, will they do so? As far as my experience goes, it indicates that there is no willingness on the part of the central stations to sell energy for anything less than the maximum price, as determined ultimately by the cost to the consumer of getting equivalent energy from some other source.

We have all heard, for years past, of the very low cost of energy in Chicago, but, nevertheless, the rates of their power contracts, as published, do not indicate that the phenomenally low cost benefits the consumer. As is well known, the large railway contracts are at the rate of $15 per kilowatt of maximum and about 4 mills per kilowatt-hour, amounting to from 6.5 to 7 mills per kilowatt-hour. Prices as low as these are obtained in Philadelphia, where the cost of coal is nearly twice as great and where no claims of great economy have ever been made.

It seems to me, however, that the argument for large savings due to the diversity factor rests upon a pretty slim foundation; the difference of from 5 to 15 minutes in the time of the occurrence of the maxima is a narrow margin, particularly when variable weather conditions are taken into account. The per cent of saving is, as the author points out, small, although the absolute amount may be great. Engineers and business men should and do base their estimates on percentage variations and not on the absolute amounts. Five per cent is just as narrow a margin when it represents five million dollars as when it represents five thousand dollars.

Bion J. Arnold: I happen to know something about the conditions of the production of power in the Commonwealth Edison station, although Mr. Insull may not think I do, but I do know that it is one of the most economical plants in the world for the production of electrical energy, and that it is due almost entirely to the splendid generalship that Mr. Insull has shown in the management and his wisdom in taking advantage of the services of the fine staff of engineers he has associated with him, and through these means he has been enabled to develop a wonderful business.

It is a fact, however, or rather I think the fundamental question as brought out by his magnificent paper is based upon the fact that a company of the magnitude of Mr. Insull's is able to take advantage of the improvements in the state of the art, by being able to discard gradually the obsolete machinery and gradually introduce more economical methods of production of electrical energy than any single small plant can do, and the large plant can stand the obsolescence loss, as it were, which the smaller plant cannot stand.

The other point is, as Mr. Insull has brought out, that he is able to increase the load factor by taking advantage of the diversity factor, so clearly shown here in these diagrams, and in that manner make a given investment take care of a much larger territory and a much larger business. Assuming, therefore, that in the production of energy he has the same station cost, he can keep the capital cost lower, and can therefore sell his current cheaper than the smaller producer can produce it.

I have recently been called into a situation in one of the large cities in this country where the power producing company was endeavoring to sell power to the street railway company, in the city, and the price had to be approved by the city. This municipality is one in which the municipal ownership advocates are very strong. If I were to name the city, you would know it as probably the leading city of that character in this country.

Therefore, the fact that the municipality, having absolute authority to approve the contract, was a party to the negotiations, in fact had the vetoing power, ought to make this particular case of some weight in this instance. The negotiations proceeded to the point where the power company made a proposition on its regular basis, embodying a gradually reducing primary charge and a reducing secondary charge, depending on the quantity of energy consumed, so as to make the proposition acceptable to the railroad, and at the same time permitting any customer to buy energy at the same rate at which the company offered to sell it to the railroad company, provided he purchased the same quantity of power. The representatives of the city said, " Oh, we can produce that power for less than that price "—Mr. Hutchinson's point. It was finally decided to leave the decision to some outside party, and the party was called in. In a short time he figured out what the railroad company could produce the power for, installing a new station, up-to-date machinery to be purchased, and installed according to the most modern methods. These figures were determined and discussed in conjunction with the engineers of the power producing company, the engineers of the city, and the engineers of the railway company. The result was that the average figure submitted by the power producing company, the company that had the energy to sell, was accepted and embodied in the contract as being lower than the figure at which the railway company could afford to produce the power itself. The price was ¾ ct. per kw-hr., delivered to the substation of the railway company, coal $1.80 per ton, taxes 1.5 per cent per annum, interest 6 per cent, depreciation at 5 per cent per annum, compounded, which is 3.02 per annum, paid monthly. That will amount to the equivalent of 5 per cent per annum. The purchaser pays this interest and depreciation monthly, and therefore the seller gets the benefit of the use of that money by putting it out at interest at 4.5 per cent and gets the full face value of the plant at the end of twenty years. The thermal efficiency of the plant is satisfactory, being 10.5 per cent, which is as good as any modern plant can be built for, although there is one in New York which shows an efficiency of 12.5 with compound reciprocating engines and low-pressure turbines, but this is an efficiency that is not attained very often. The investment per kw. capacity in the plant, however, must be considerably higher than the modern station can be installed for, so that its gain in thermal efficiency is probably offset by higher fixed charges.

Take the stations installed several years ago. Their thermal efficiency ran from 7.5 to 8.5 per cent. The modern stations run from 9 to 12.5, mostly running between 10 and 11¼ per cent. That is about as good as we can do when we start out today to design a plant and turn out energy for the purpose of running our railroads, especially in sizes of 10,000-kw. capacity. If we can go to 15,000, 20,000, 25,000, or 30,000 kw., we can bring the cost per kilowatt-hour down somewhat, not because the thermal efficiency increases so greatly, but because the labor and capital costs decrease somewhat. The thermal efficiency of the plant, after you pass 10,000-kw. units, remains practically constant. The cost per kw., that is, the fixed charge, might go down somewhat, because you could buy the larger unit for less cost per kilowatt capacity, so that you get a slight reduction in the fixed charge and a slight reduction in the labor cost, but the thermal efficiency remains practically constant, consequently there is not much chance for reduction of cost there.

Therefore the central station, built and operated as it is, with skilled managers, skilled engineers in every sense, and having an enormous investment, is able to take advantage of all these conditions and to keep increasing its investment by installing large units, but at small cost per kilowatt capacity, and thus keep its fixed charges down to a point below the point a private plant can reach. That is the reason why the large stations can sell energy cheaper than we can make it in small plants.

Mr. Insull referred to one situation in New York, viz., the New York Central, in which, he said, the engineers did not know that they ought to buy energy and the sellers did not know they ought to sell; all of which is largely true. It is a fact, however, that at the time those plants were installed, some eight or nine years ago, the thermal efficiency of plants was about 7 to 8 per cent, and at that time Mr. Insull was running turbo-generators, some of the first in the country, on some 24 lb. of water per kw-hr. He has advisedly discarded these generators since, putting in machines that are running on, say, 12.5 lb. of water per kw-hr. Those of us who built the stations at that time could not do as well as this, although we did buy machines at that time, which we installed, which produced a kw-hr. on 14 lb. of steam, and the next station we installed is doing it on 12 lb. of steam, so that we did not do as badly as some might think. We may have made some errors at that time, but the *main things* pointed out *now* as *errors* were *not errors*. They were decisions that had to be made due to the conditions which existed at that time. The central station was not in position to sell energy at that time as cheaply as it can sell it today. Therefore, we could not secure a price which would warrant us in buying the energy, hence we had to build plants. We did build the plants, and fairly economical plants, and one of those plants which is in existence today is the most economical railway plant in this part of the country, running on about 40 per cent load factor, so we were not very far behind Mr. Insull in that particular plant at that time.

Samuel Insull: Are those the same machines we scrapped?

Bion J. Arnold: No, you scrapped 24-lb. machines and we put in 14-lb. machines.

Samuel Insull: We scrapped a 17½-lb. machine as well, made later than the machine to which you refer, and for which we paid a premium. I understood this machine was the same as you installed.

Bion J. Arnold: I want only to make this brief conclusion: I think Mr. Insull presented a splendid paper, and I am in sympathy with the policies he is advocating. In my capacity as chairman of the Board of Supervising Engineers, Chicago Traction, I approved the contracts the Commonwealth Edison Company made with the railroad companies in Chicago, and approved them because I knew we were buying energy as cheaply as we could make it. My advice to clients for some time has been, " Whenever you can buy current as cheaply as you can make it, buy it, and get rid of the worry of producing it; if you cannot buy it more cheaply than you can make it, then get ready to make it, and the man who has it to sell in large quantities will then come round and show you that he can sell it to you more cheaply than you can make it."

Frank J. Sprague: We are face to face with two important facts which are not altered by any minor discussion as to individual cases. First: That throughout the length and breadth of our country we are facing a continually increasing demand for power —increasing for two reasons, first, because of the inevitable increase of population, and second, because of the increasing uses for power. There is also the somewhat appalling fact, if we take account of the future, instead of being satisfied, as English directors of railways are, to let posterity take care of itself, a decreasing supply of fuel within the limits of our present ken. What does it mean? That we as engineers, not, perhaps, so urgently for the present, but for the future of those to come after us, must seek every opportunity to conserve our available power, now burdened with uneconomical production, and avoid the wasteful use of that power.

Mr. Insull has helped to blaze the way by the work which he has done in the Commonwealth Edison Company, in increasing the efficiency of power production and the variety of uses; and I look forward to the time when, in place of the thousand and one small isolated plants for different purposes, this country will be covered by great interconnected central stations, not individually magnified to an undue limit, but of such size as working efficiencies may demand.

If one should, on a cold day, in the city of New York, go to one of the upper levels of one of our great office buildings, and look northward, he will see countless steam jets in the air, every one coming from a non-condensing isolated plant, operating either electric lights or elevators or machinery of various kinds. Suppose, for a moment, we could blot New York out of existence and recreate it tomorrow, would there be one of these isolated plants in existence? Would we have the diversity and irregularity of production we have today? Certainly not. New York would be planned so that not only its light but its power, and a large proportion or perhaps all of its heating (and, mark you, heating is one of the greatest futures in the electrical field), would be supplied from a few great central stations.

It was only a short time ago that New York was on the verge of a water famine, and our Commissioner of Water Supply, Gas and Electricity informed us that the consumption of water was 125 gal. per day per capita. I wonder where the 125 gal. per capita went to. When I think of the great population of New York that goes out of it in the summer time, and the proportion whose use of water is restricted, I could not find that there was an average of 40 gal. per capita per day used in the necessary domestic requirements in the City of New York. That left something like 85 gal. per capita to be accounted for. Part of it goes to waste in leaks, but a great part of it goes into the sewers of New York, because the power plants of the city, other than its great central stations, are run as non-condensing plants. With these eliminated I imagine our per capita use in the City of New York would not be more than 75 gal.

I commend that proposition to some of the members of the Institute as a suitable subject of study and investigation.

Mr. Insull has raised the question of the lack of foresight of the New York Central in not arranging to buy the necessary power. We could not buy power at the time we arranged for the New York Central stations under any admissible conditions. But I desire to acknowledge the very great debt which we owe Mr. Insull, because when the committee of engineers representing the New York Central Railway went to Chicago, the first thing they did was to go to the power plant of the Commonwealth Edison Company, where the first 5000-kw. machines were being installed, and were not then, I may say, fairly in running condition. As I stepped upon the platform of one of these turbines I turned to my associates and said, "I care not what difficulties stand in the way, or what may happen here at this plant, the day of the reciprocating engine in the electric field where steam is to be used is past, the day of the turbine has come." The decision of the New York Central to adopt turbines was made at that time.

Charles P. Steinmetz: I wish to refer to something which has not been mentioned in this discussion, and mentioned in the paper only by implication in the introduction, although, I believe it is an important factor in the success of these big central stations. It is an additional diversity factor beyond that which Mr. Insull has mentioned, and that is the diversity factor of the engineering staff. A system as large as that in Chicago can afford to have in its employ high-priced engineers of the highest theoretical knowledge and practical experience and general ability, far beyond that which any one of the smaller component plants could have, and that, necessarily, must give the big system an advantage which none of the smaller ones could possibly enjoy. That is a diversity factor which is not approaching constancy with increasing size of the system. The thermodynamic efficiency may approach constancy, the diversity factor of load may approach constancy, but the diversity factor of engineering staff does not approach constancy, but remains of the same value, no matter how large the system grows to be, and that is an advantage which the smaller systems cannot hope to vie with as against the big system.

Bion J. Arnold: One point should be added to Mr. Insull's plan, over and above all the technical propositions which have been pointed out. There is a broader question, which Mr. Insull foresaw before any other man I know of. I think we will all credit him with it. That is, he foresaw that the public service business is a natural monopoly. He reasoned thus: "I am entitled to a monopoly. I am willing to invest, for any monopoly, a reasonable total sum, but I want that investment protected. Protect my investment to the extent of six or seven per cent, or any other return which may be considered reasonable, and I will keep furnishing power and keep cutting down the cost of power to the point that will bring that return." That is the broad policy which has won the great success of the Commonwealth Edison Company in Chicago, combined with the great engineering talent of which Dr. Steinmetz speaks.

Samuel Insull: I think Mr. Stillwell asked me whether I would be inclined to operate a unit fifty miles from the base of supply in northern Illinois—I don't think it is possible to find a place where that would be necessary, although I have not had the experience to be able to state whether it would be a safe thing to do or not. I would have to refer Mr. Stillwell to some of the people more familiar with long distance power transmission than I am. I do not understand Mr. Stillwell's reference to large central stations.

Lewis B. Stillwell: What I meant to point out is this. As shown by your curves, the advantages accruing from the diversity factor, in consolidating plants with reference to their supply, decreases as the size of the plants which are aggregated increases. In combining 10-lamp loads you have a high diversity factor. When you get to dealing with large plants, and undertake to realize an economy by reason of putting together two 50,000-h.p. plants, for example, you do not get a great deal of advantage from the diversity factor under ordinary conditions. I think your curves bear that out.

I would ask you again the question that I endeavored to make clear in regard to this supplying of power at a distance. You are in a position to look at the matter from both sides of the question. The very practical question that presents itself many times to us, in the present state of the art, and the art is not young, is this—Is it wise to endeavor to supply all the lighting of a city, a city of 100,000 people, from a transmission line 50 miles long, or should we let the lighting alone and let that be taken care of locally?

Samuel Insull: I do not know that I can answer that question, because I have not had the experience necessary to enable me to answer it.

Lewis B. Stillwell: I understand you are contemplating doing what I have endeavored to describe.

Samuel Insull: No, I do not think there is any place in northern Illinois where we would be more than 20 miles from the source of supply. It does, however, happen that we are supplying a number of consumers 30 to 40 miles from the base of supply, temporarily, and it happened last summer that we brought coal from the coal mines up to Chicago and turned the coal into energy, and sent the energy down to the coal mines to help raise coal out of the mines. But those are isolated instances.

Lewis B. Stillwell: That is not the same point at all.

Samuel Insull: I really do not know. I understand it is being done on the Pacific coast. Personally I have had no experience in the matter. I think probably I would be inclined to try it, keeping my local plant as a reserve, possibly using it a part of the time, so as to save the expense of banked fires, and get a portion of my energy from outside. I would creep before I walked, I think. After I got confidence, later on, in the transmission line, I might finally dismantle the plant.

I stated in my opening remarks that the percentage of saving was low, but that that low percentage amounted to a very large sum of money. I simply picked out that illustration of diversity of the block of apartment buildings because it occurred to me that possibly there might be some gentlemen here who really did not understand what was meant by diversity factor. I am not a trained engineer, and it took me quite a long time to learn what it meant, and I thought there might be some here who did not understand it and would not care to confess it, and I thought I would show them the best and plainest example that I had.

I was dealing with the matter on a broad basis. Probably outside of the very large traction companies in Chicago, I am one of the largest purchasers of power in this country.

There is no steam plant I have been able to discover where people pay commercial prices for fuel where they can produce current at 2.5 mills. I cannot do it. If there is any engineer, a member of the Institute, who can design such plants, unless some one has a longer purse than the company I represent, I shall be glad to retain him.

In dealing with the situation I have naturally had to refer to New York. It is the subject uppermost in your minds. So I took New York as the basis of my figuring and backed it up by the results we have obtained in Chicago. But it matters not to me who is the owner of the generating plant and the primary transmission system. I do not care whether it is the local lighting company, whether it is the local railway company, or whether it is the steam railway company, the principle is the thing I am contending for. I am contending against economic waste. When I speak of " purchased power " I simply use that term because that is the term that has come to be used in the industry as designating the difference between making your own power and buying it from some one else. I say again that I think it would be a great misfortune if, as the result of this meeting, or as the result of the agitation that is going on throughout the industry on this subject, some move is not made with reference to concentration of manufacturing and primary distribution. I think one is almost as important as the other.

There are some other serious questions of an engineering character to be decided within the next year or two on this subject. I do not know at this time what the limit of size of unit is that will add to the efficiency, or the limit to which we can go in the increase in efficiency of the unit. I have not been able to find out myself. I have consulted the best experts I can find on both sides of the ocean. The question of size of unit comes in very much in this question of concentration of production of energy. I do not think we have by any means reached the economical limits of the cost of production. I do not think it will be possible for any ordinary public service company, by itself, doing just its own business, to take advantage of the economical limit when we do reach it. I think it can only be done by an aggregation of production.

There are a good many things we can learn to advantage from our neighbors. I have been for a good many years in the habit of sending my engineers to Europe to see what they can find out. If you meet them on the train between New York and Chicago when they are returning, they will tell you that they are behind the times over there, and that we cannot find out anything from them which would be an improvement on our methods, but when we get the written reports of these experts we find that we get full value for the expenses of the trip. I do not know of any case on the other side where steam railroad electrification on any considerable scale has started and the railroad companies have built their own generating stations. They go a great deal closer into the economics of things than we do in this country. We make money more easily here, we have greater markets. We can take a lesson from their experience. I make one suggestion to the Railway Committee—Take the remarkable situation you have here on the Atlantic seaboard, with the greatest density of population in the small amount of territory between Philadelphia and Boston. Take Philadelphia, New York and Boston, stretching out as three fans, with places like the Connecticut manufacturing towns, and go along the Boston & Albany road to Albany, and then cross New Jersey, through Pennsylvania to the south of Philadelphia. Figure out the money that can be saved by putting all the generation and primary distribution of power in that territory under one ownership. I do not care who owns it, whether it is the railway company, or the lighting company, or the traction company, but I venture to say that the amount of money you would save would not only be sufficient to build the transmission lines and the generating stations of steam railroads in that territory, but, I think, would go a long way towards equipping the railroads themselves.

Hans Lippelt (communicated after adjournment): No doubt most of those who have read Mr. Insull's paper have appreciated the valuable evidence and facts brought out. The first impression produced is certainly favorable towards Mr. Insull's proposition of unification of power stations. After all, it has occurred to me to question if an increase in efficiency and savings, by the means proposed, is really wanted. You may think that this question is absurd, because any saving of money is usually welcome at any time. I believe, however, that in this case the savings are to be paid for at too high a price.

Consider first the reliability. If for greater New York all the electric stations for light, heat and power and for railroads, etc., were united into one and a boiler would explode, be it by carelessness or bad will, who would guarantee that the fragments of the boiler would spare the vital parts of the power station? There have been cases where, through a much smaller breakdown than a boiler explosion, enormous damage to the power house was entailed. If, for instance, the switchboards were destroyed, the whole big district connected to it would be without further supply of electricity. What would then be the consequences? Can you conceive all of them?

In case of a general strike, similar to the recent coal strike, or in case of war, would the big power house not be a great temptation for some aggressive people? Of course you do not expect a war here, so you may consider, if you like, your power house safe from such troubles. But for how many years can you guarantee such safety for your supply of light, heat and power, and for your railroads? May the railroads not be put out of business just when they are most urgently needed?

Moreover, I believe that with the realization of Mr. Insull's proposed scheme a legal reaction would set in, based upon the Sherman law. How would you be able to show that there is no " unreasonable restraint," in order to evade prosecution? Would not the trend of unification tend toward " restraint of trade " in electricity?

When I saw the slides, showing the present power stations, disappear and the others, showing the unified systems and common power stations, appear in their places, I felt that with all these power stations there had been wiped out many positions and opportunities for people who are compelled to offer their abilities and skill for just such opportunities to make their living. The vast scheme would not only affect the oilers of the machines, but all grades of employees from the oilers up to the clerks, engineers, managers, etc., would be affected. Would those who were told to go, praise the scheme as a wonderful stride forward in civilization? Would they?

It was remarked in the discussion that the great managing company could afford to engage " the best engineer," pay him a good salary and have him devise the best methods and means. What is to become of the other engineers of reputation in this line of business? Is their talent to be wasted? The market for it will then be quiet and the choice small. With only comparatively few power stations in the country, where is the next best engineer, where are others, going to get their experience? Are you sure that the ablest one will get his opportunity to develop his capacities? Would the few men higher up always favor applicants on the basis of merit and thus insure the expected high standard of efficiency?

If unification of power houses is so economical, why then shall we not go a step further and wipe out not only the individual power stations, but the Pennsylvania, the New York Central, the Lackawanna and other railroads and make them all one? According to Mr. Insull's theory and, as stated in the discussion, according to approved practical experience, the savings must amount to many millions of dollars. Yes, and to go beyond the limits of this horizon, why not save money by making the states of the United States one big state? Would you feel safe and justified in advocating such schemes, standing just on Mr. Insull's theory, or would you need a broader ground to stand on? Would you not discover new factors entering into the proposition and limiting the great hopes for a wonderful result, which should benefit all the people of this free country? It seems to me that the speaker himself had a premonition of the dangers slumbering in his scheme, when he spoke of the " courage " that would be required to realize such a vast thing. It will certainly be interesting to see when the first steps in this direction will be taken, and how many of them.

Discussion at Boston, Mass., June 26 and 27, 1912

Frank J. Sprague: It has been said that the Railway Committee has been somewhat inactive during the past year. I have purposely held it in that position. It seemed to me, in the beginning of the year, that we were in a state of development in respect to the three systems of railway operation, the polyphase, the single-phase and the direct-current, and that with regard to each of them there was a good deal to learn, and each had a good deal to demonstrate. Extensions along the lines of each of these systems were contemplated at that time which might make it possible for us to make comparisons which heretofore had been impossible. It seemed to me wise during the year to suppress a good deal of the discussion that had taken place as to " systems," that little was gained by its present continuance, but, that if we proceeded to determine the actual facts of performance as illustrated by those systems which were then in operation we would lay a basis for future progress which would be more reliable than anything else we could do at that time. It seemed to me that one of the first things to do in getting information was to secure the facts as to the cost of power at the central stations; and in casting about to get authoritative statements on this subject, I found there were two sources. One was specifically a railroad source, or combination of railroad sources, the operation of the plants at Port Morris, Cos Cob, Westville, Marion, Jersey City and Long Island City, each of which was doing little else than supplying current for railway purposes. The other, of course, was the central station operation of the country as typified in Boston, New York and Chicago, perhaps to the greatest extent in Chicago, because there not only does the central station company have, in addition to the lighting load, a diversified supply of power to all sorts of industries, but also a very large railway load. So I appealed to Mr. Insull to prepare a paper on the question of the generation of power for electrical purposes, which he kindly consented to do, and also to supplement his paper by statistics relating to the railway conditions in Chicago, which are important.

Although the Railway Committee, as such, has been to a certain extent idle—its visible work is typified in Mr. Insull's paper—it has not been idle, through its chairman, in other directions. I have been charged with being an ardent advocate of this or that system, in a somewhat competitive way. I have stated sometimes that I was an agnostic, and I have hoped that there was some other means of arriving at results than by the somewhat accentuated discussions which we have sometimes had. So I have been centering my energies for the past six months on trying to bring about something of an *entente cordiale* between certain railway companies and the larger manufacturing companies, by which they would agree to take up some great railway problem, and present it to some acceptable technical commission whose members should be *persona grata* not only to each other but to the manufacturing companies and the railway companies. If the problem included terminal work, freight haulage, and suburban and through passenger operation, and extended over sufficient territory to embrace all kinds of railway contingencies, probably these men could divest themselves of any past prejudices which they may have had, and recognizing that both single-phase, polyphase, and direct-current applications have now reached nearly their normal limits of development, so far as motors and transmission and all those matters are concerned, could arrive, perhaps, at sound conclusions as to the future of electric railway operation.

It is my opinion that this proposal has somewhat advanced, and I believe that if any competent body of fair-minded men will divest themselves of their other activities, and confine themselves for some time to the consideration of a specific problem, they must arrive at one of two conclusions: first, that there is a definite trend of development in certain directions, or second, that the applications of electricity are so varied and its possibilities so catholic that while we are not confined to any one system there are certain things which may and ought to be standardized.

I believe that such a body of men with all the facts before them would come to a common conclusion, no matter how much they differed in the past. I do not predict, at the present time, what that conclusion would be. The principle of the survival of the fittest will apply to the electric railway systems as to everything else.

When I took up Mr. Insull's paper I was very much impressed by two statements which I will quote. One of them begins on the third page of the paper: "The conclusion that I have come to is that the concentration of the production of energy, for all purposes required in a given area about any large center of population, would result in such a saving in capital, and such a saving in operating expenses, as to provide sufficiently for the generating capacity and primary transmission systems necessary to electrify the terminal systems and suburban service of all the trunk lines centering in and around that center of population (particularly is this true of New York), and such a saving as to yield very large profits, in addition, to the engineers and financiers having the courage to handle so great a problem."

The other statement is found on the first page, where Mr. Insull says: "Nor am I going to discuss what might be termed the technique of the electrification of steam railroads; that is, the special system that should be used, whether it should be done with one class of current or another, or one pressure or another. The system finally decided upon must be the one which fills conditions of railroad operation, and at the same time renders it possible for the railroad company to take advantage of the sources of energy supply already existing, as the railroad demand is only about 15 to 20 per cent of the total demand for energy in any community."

In Chicago there has been for a long time a popular movement for the electrification of the steam railway terminals. That movement was initiated very largely because of the smoke conditions which blanket that city close to three hundred and sixty-five days in a year. With some thirty-two railroads entering Chicago, and with a very diversified freight and passenger service, it goes without saying that if these several railroads should proceed independently, and each settle upon some independent system of electric application for its service, there would not only be an intolerable condition of confusion in the end, but there would be such a sacrifice of initial capital invested as to make electrification burdensome and impracticable. Until the investigation was made by the authors of the appendix to Mr. Insull's paper, the amount of power which would be required in the electrification of these railroads was practically unknown, but as we note the amount which is required, as set forth in the paper, we see that the average is exceedingly small, when we consider the size of the generating units used today in our modern power houses. For example, we find here a record that the individual average load in kilowatts for freight service, in October, 1911, varies on these thirty-two railroads from a minimum of 100 kw. up to a maximum of less than 8000 kw.; also that the average maxima of all these loads in that particular month was only 72,000 kw., which is only the capacity of three or four modern generators. Mr. Insull pointed out the possibility of supplying power to these railroads. For that supply an individual power house to each road is simply out of the question, it cannot be considered. Group supply, that is, power houses which are intended to supply all the demands within a certain area, is the next step, and offers a gain in first cost and economy of operation. Centralized supply, centralizing not only power but transmission lines and diversity loads, offers so great an economy, not only of initial investment but in operating expenses, that it does not seem to me that there is any possible question but that the future must see that solution in Chicago.

I suppose the majority of those who read this have not seen the first report of the commission which now exists in that city. Sometime ago the railroads in the vicinity of Chicago, co-operating with the Association of Commerce, appointed a commission whose province it was to study the abatement of the smoke nuisance in Chicago and the possible electrification of the railroads. An elaborate organization was created, and the first product of the work of the commission, after a year's activity, is confined to the investigation of the smoke nuisance, how existing smoke conditions can be combatted and overcome. Electrification of the steam railways, so far as that report is concerned, seems a long way off.

How is that prospective delay to be overcome? By appeals to the prejudices of the railroads, or to those of the manufacturing companies—especially in view of the differences between the engineers? Surely not. It is my belief, however, that there is an effective procedure—that there can be created, between the railroad companies and the manufacturing organizations, an independent financial organization which, after due investigation of railways where electrification may be seriously considered, is prepared to go to these railways and say: "Gentlemen, you may not believe in electrification, and you may not care to take the necessary capital risk, or divert your capital from your other undertakings, and you may not be fully convinced of the financial returns which will come from electrification, concerning which others are more confident than you are. We are prepared to enter into a contract with you to operate your railway on the basis of supplying power for a period of years at a reasonable rate. We will also, if you desire, make a contract to supply on a basis of usage the rolling stock and equipment for your railway, leaving you to provide a right-of-way along your track for such transmission lines as may be necessary, and only such capital investment as is required for the working conductors, or the possible provision of substations along the right-of-way if such be needed, thus limiting the capital risk of the railroad to about one-third of what would be required for individual operation." I am frank to say that that possibility is in the future, and it looks as if such a thing may come about.

Referring for a moment to the cost of power, I notice that Mr. Insull criticizes the New York Central and Hudson River Railroad management, and inferentially its engineers, for having installed power houses. We did not have Mr. Insull and his company to deal with in New York. We were face to face with the necessity of putting in a power supply which could not break down, or if it did break down we should have another one to fall back upon. Positive insurance of operation and ample supply of power were primary necessities, no matter what the cost, so long as electrification was to be undertaken, as it had to be under the law. The result was that two great power plants were installed for the New York Central and Hudson River Railroad, one at Port Morris and the other at Yonkers. The station at Port Morris is pretty well loaded, and had the project of electrification proceeded as fast and as far as originally laid out the Yonkers plant would be likewise loaded at the present time. But we did try to increase our load by offering to our friends a supply of power, provided the supply of power would be in accord with our own belief as to what was right and proper. That did not materialize, and the result was that the New York, New Haven and Hartford Railway built its own power plant. We had to build our own power stations because we could not get a proposition from anybody to supply power at a reasonable rate.

The output of the Port Morris, Long Island City, Westville, Jersey City, Marion and Cos Cob power stations varies roughly from 21 million kw. in 1910, in the case of the Jersey City station, to 159 million kw. in 1911 in the Marion station; and the power costs, according to the curves of the principal stations, run along at a very fair average. For the year 1911 the average cost of power at five of these stations was about 0.51 cent per kw-hr. at the station switchboard, excluding fixed charges, etc. The lowest average seems to have been at the Marion station, 0.45 cent per kw-hr. Those familiar with the cost of power at the Commonwealth Edison Company's plant, and even taking into account the difference in the cost of coal, an advantage which they have, will find that the average of 0.51 cent per kw-hr. is higher than is achieved at the larger station with large units, with a very diversified use. The Cos Cob station, for reasons which I have not yet been able to determine, runs from 45 to 60 per cent higher in power cost than the average of the other five, and varies considerably. That is a single-phase operating plant, but I do not know how much that has to do with such a variation between that and other stations.

We have here the statistical facts, but I do not wish to make any prediction, or come to any present conclusions as to this difference of 45 to 60 per cent between the average of five stations and that of another station. The character of the load may have something to do with it. The Cos Cob station ran only something like 27,000,000 kw. for the past eleven months, and if that is the reason, it illustrates the attitude which I have taken all along, that since there was an opportunity to buy power from an existing station at the time that Cos Cob station was erected, probably, so far as operation at the present time is concerned, it would have been more economical to have bought the power than to have erected and operated this central station.

H. G. Stott: I have read this paper with great interest and I have been trying to discover the hypotheses from which Mr. Insull draws his conclusions. As far as I can discover, his conclusions are based on the results obtained in Chicago. These results, it must be remembered, were obtained, not by combining first-class plants, but by combining in one or two plants the output from a number of practically broken-down plants which were just about ripe at that time for reconstruction.

To begin with, the railroads in Chicago were operating plants which were of antique design (several of them non-condensing) and had been allowed to run down, and necessarily operating costs were quite high, whereas the Commonwealth Edison Company had just concluded installing the most efficient apparatus that could be found on the market. It therefore had all the advantages of a modern plant as compared with an old plant. This, in itself, would probably give an advantage of from 30 to 60 per cent in operating costs.

Referring to Fig. 15 in his paper, the author says " This diagram shows you the result we have been able to obtain." The diagram does not show costs; it merely shows the difference in what might properly be called the load factor, which shows that they have succeeded in filling up a gap in the load. I have for a long time been trying to discover the relationship between load factor and cost. As the first approximation to a law governing it—an empirical relation—I find it varies inversely as the fourth root of the load factor. That means, as shown, for example, in Table III, where a comparison is given of the average of the load factors as 51 per cent, but where, combined on one generating system, the total load factor would be 56.2 per cent, that if you use this rule of the inverse fourth root the saving in operation should amount to about 2.5 per cent. This, when applied to the data for the total annual load in the district covered by Mr. Insull's paper, which covers New York and the neighboring district of New Jersey, shows that the output is practically 2,000,000,000 kw-hr. per annum. Applying this figure to that output, we get a saving of $250,000 per annum, as against $1,000,000 in the paper, assuming a cost of 0.5 cent per kw-hr.

From this brief analysis, I have concluded that Mr. Insull must have assumed that the results obtained by any combination of plants would be the same as obtained in Chicago, irrespective of the condition of the plants, and on this point I take issue with him. You come to a point where the size of the unit used no longer affects this economy appreciably. For example, in a 10,000-kw. turbine unit, using high-speed modern machines, you get almost as good economy as you can in one double the size. When you reach a point where you are using that size of unit, very little is gained by increasing the size of the station. You make a slight gain by reducing what might be called superintendence or overhead expenses on that plant, but that is trivial and, being spread over the output, ought to have very little effect upon it. I have come to the conclusion that there is practically nothing to be gained unless you can change your load factor very perceptibly. When you get beyond a 50,000-kw. plant there is very little to be gained from an increase in size alone.

The diversity factor in railroad work, as we notice from the paper, is practically nil. Peaks, as shown by the load curves of the periods, are almost exactly coincident throughout the year. No matter how many plants you combine in one, the total installed capacity must be the same. Mr. Insull mentions that with independent plants for each road he would call for a reserve capacity of 50 per cent, whereas with the single combined plant he only calls for reserve of 25 per cent. I would like to ask him if he follows the same rule, and where any one actually carries 25 per cent reserve in a plant? With modern apparatus, 15 per cent reserve is, perhaps, all that is necessary. One unit is considered ample when combined with the overload capacity of the other machines.

Another point on which I wish to take issue with him is the statement in regard to the saving on the distribution system. No matter how many plants you have, considering the question broadly, the cross-section of the copper required to carry the load is practically the same whether the combination is made up of two plants or forty plants. Each distinct plant will require a certain cross-section of copper, irrespective of the fact that it is in combination with others. I am speaking of the total cross-section, not the total length of cables. The saving in distribution in conductors which Mr. Insull has shown is not a factor of consolidation of plants; it is a factor of distribution of plants at better feeding points. For example, if we take the various plants, some fifteen or sixteen, around New York, and one came to an agreement with the other and said, " We will feed all substations or networks within two miles (3.2 km.) of our station, and we will agree to interchange power on that basis," you would obtain in that way all the saving it is possible to make in the use of copper, without combining them in one mammoth plant. In a mammoth plant the total amount of copper required would be enormously greater than in several smaller plants.

The old problem of finding the center of distribution for a given load is a familiar one, and it shows that the plant should be put in the center of distribution to effect the maximum economy in copper. The cross-section is practically the same, where you have one or more, except that if you have one large station, you will require a larger cross-section due to the increase in drop, on account of the longer feed.

I am sorry, also, that Mr. Insull has not told us, or given approximate figures, even percentages, if he did not care to disclose actual figures, of the financial result of this diversified load factor which is obtained by combining the plants. The question immediately comes up: Suppose a plant gives six mills per kw-hr. as the operating cost, and we are able to erect one which will operate on four mills per kw-hr. or less, and sell power to the other plant, is not the man who now has a plant obliged to amortize his investment in some way? For that investment stands on the books and represents collateral value for the bonds which have been issued for the construction of the whole road or system. If we write off that capital immediately, as we do when we shut down the plant, and virtually turn it into scrap, at ten per cent, probably, of the original cost—you are very lucky if you get that—should not the customer, who writes off that capital, share in the profits which he has enabled the manufacturer of power to make? Therefore, the profits apparently should be divided. That is a point of view which I have had brought out very forcibly in connection with some of our companies, that you cannot turn around and say, merely because you can supply power to such a company, perhaps, at 25 per cent less than the cost to them of making it, that therefore they should throw out their plant, because, obviously, they have nothing left to show as collateral for the bonds that that plant represents. The profits must be divided on an equitable basis between the company which makes the power and the company which buys the power.

In conclusion, it would seem to the speaker that the ideal solution of the power question is for each company to retain its own plant, thereby preserving its equity, and let an agreement be made by which each plant will supply *all* power within its own zone of economical distribution.

It is, of course, assumed that the plants will be modernized and kept up to the highest point of efficiency, for if the common exchange price per kw-hr. is put low enough by agreement, then each company will be forced to make its power as economically as possible.

William McClellan: It is well known that railroads may be divided into classes from the standpoint of electrification. Some roads will probably not be electrified until conditions very greatly change. For another class of roads a large amount of study would be required to determine definitely whether they ought to be electrified. There is a third class of roads which ought to be electrified at once if their managers could do so.

The first class of roads will have to wait for consideration until conditions change or until they perhaps become a part of a larger system and are electrified as a matter of general system economy. As to the doubtful class of roads, there is no question that a larger and larger proportion of the doubtful roads can be electrified when our costs are reduced. By costs here we mean not only the direct costs of operation but also the cost of investment as reflected in the interest and depreciation charges. There is no question that if the financial test were applied at present the answer in many cases would be negative.

But where can this cost be reduced? Certainly we cannot expect electric locomotive costs to be much reduced. True, they have been higher than they will be in the future, especially when prices are standardized and larger quantities are manufactured. It must be conceded, however, that there will be no great saving in this item.

The third-rail system has been standard, more or less, for a number of years and its costs are now down practically to rock bottom. There can be no saving here.

The overhead high-voltage catenary system at first was very expensive, but no one making an examination of what the New Haven road proposes to install now could possibly call it expensive in first cost or expensive to maintain. It may be safely claimed that no great reduction can be expected in this part.

I am not unmindful of the great saving brought about by electrification through the increased use of both track and equipment. It is not necessary, however, to discuss this here.

Where, then, shall a reduction in cost be looked for? If the above statements be true, decreased cost can only be brought about by increased efficiency. It is not surprising, therefore, that combinations are proposed with the idea of obtaining this desired increase in efficiency. For a number of years rights-of-way have been combined to make operation as easy and convenient as possible. As a consequence the railroads of this country make up one great network, all, or practically all, of the same gage.

In a way, there has been a combined use of equipment by through trains, but the only great example of this is the Pullman system. When we commence to study electrification there seems no good reason why there should continue to be the diversity of equipment which now obtains in these operations. There is no reason why a railroad desiring to undertake electrification should design its own type of cars, differing only in detail from the cars on an adjoining system. A group of railroads operating in any one general territory could well agree to have one type of car and one type of equipment, for each particular kind of traffic.

Mr. Sprague has acknowledged that he asked Mr. Insull to write this paper because he thought the capital investment might be reduced by having the power supplied from one general power house for a large variety of uses rather than from separate power houses. I think this possibility does exist, but conclusions should not be jumped at too quickly. I am rather inclined to agree with Mr. Stott that we have gone somewhat far afield in this matter and have not given proper study to the question of substations. It should be remembered that the only reason for establishing our modern substation system, that is, one power house leading into a number of separated substations, is that such a system puts a better load factor on the power house than a series of power houses would have had, one at each substation. If, however, the time comes when increasing the size of the station does not decrease the cost of production, then it is almost obvious that the substation system need no longer be adhered to.

It is quite probable that the total cost of transmission from a mammoth station to very large substations might be in reality an added cost. Under these circumstances the cost of power at the point where it is used would be greater than if separate power houses, properly located, were established.

The reference to sharing profits between the large companies and the smaller companies buying power is interesting. Certainly the buyer in making his contract for power would have to see to it that the price he got was such as to permit him to amortize his old equipment and retire it in a given time. If this point be included it may be more difficult still for the large power houses to make a showing in those cases where amortization would have to be allowed for.

Percy H. Thomas: I do not know that I can add anything of value to this discussion, except to suggest that possibly one reason our railways are not more in a hurry to go ahead and electrify their systems is that they are waiting to see if some new development will not turn up, some new method of operation appear. We cannot assume that we have obtained the best solution of every problem. We have made great advances, but still there is the question, " If we wait five years more, may we not use a different system?"

In my opinion, while much may be said on both sides of the question as to whether a single central system can better supply power for all purposes than a number of independent systems, we can almost foretell the actual result by instinct—the trend since the industry began has been towards centralization. We cannot always state just where its superiority comes in, but taking all the factors into account, I believe that centralization of control is what we are coming to. I feel very sure that at least our local population centers ought to be supplied all under one management; it may be that the advantage is not primarily on account of diversity factor, it may be that it is not on account of load factor, but there will surely be found some basic reason for justifying this method.

W. G. Carlton: There is one point Mr. McClellan brought out in regard to pooling electric cars and locomotives. I think the idea of pooling might be applied to the power stations, for example in New York City, and if that were done, then the idea of Mr. Stott, in regard to saving distribution expenses by assigning territory to any one station and letting that station cover the load in its vicinity, could be very readily worked out. It seems to me that, as far as New York City and vicinity is concerned, if there is any large saving to be made in the handling and distribution of power in a wholesale way, it has got to be done by "pooling" the power stations. As to the manner in which that can be best worked out, I have nothing to suggest at the present time. I do not, however, believe the time will ever come when it will pay to build much larger power stations than we already have in some cases in New York City.

Calvert Townley: This question of the concentration of power in large centers, which is the underlying thought in Mr. Insull's paper, is, as he himself states, not a new one. It has been studied for a great many years not only by engineers but by the financial men interested in properties which supply electricity. Mr. Insull ably states many reasons why it is cheaper to generate a large amount of power in one station rather than smaller amounts of power in several stations, but he does not prescribe any limitation to this concentration process.

Suppose we carry that argument to its logical conclusion, without any limitations at all. If it be true that it is better to generate all of the power in Chicago or in any other large city, in one big station, why is it not true that all of the power in the suburban territory around that city should also be concentrated, and extending the argument still further why is it not true that all of the power required in the state, or in a group of states, or in the United States, if you please, shall be generated by one station located in Chicago?

Of course the absurdity of that conclusion is seen at once when it is stated, but it is necessary to bring out and strongly emphasize this point that any treatment of the problem of power generation is incomplete and faulty which does not also fully consider the question of distribution.

Certain economies referred to in the paper are obtained by increasing the size of the generating units. Others result from a higher diversity factor, and in many cases savings may be effected up to a certain point by combining into one the several distributing systems. As Mr. Stott points out, however, little is to be gained in operating economy by increasing the size of generating stations beyond a certain point, so that in considering a power supply of the magnitude of that under discussion the argument for concentration to secure operating economies has but a very limited application.

Mr. Insull's paper lays great stress on the improvement in the combined diversity factor over the several individual diversity factors. Mr. Stillwell pointed out, in the discussion which was had on this paper in New York, that as the size of the power stations which are combined increases, the probable improvement in diversity factor decreases. This would seem to be almost a self-evident proposition, even if it were not supported as it is by the very complete set of curves given in the paper. Having therefore reached a limit in saving due to increase in size of the units or stations which are combined, and having stations so large that their combinations will show but very little, if any, saving, in the diversity factor, it becomes difficult to find good argument in support of further concentration.

A comparison of the two maps of the city of New York and surrounding territory given in the paper, one showing the number of stations now installed, and the other the number which ought to be installed, shows that the author does not suggest combining all the stations into one, but believes several are to be preferred. The reason for retaining several power stations, instead of concentrating the production of power in one station, is not given in the paper, but it is a fair assumption that the author's examination of the local conditions indicated to him that the possible economies to be effected by further consolidation would be more than offset by the increased fixed charge of an enlarged distributing system and the losses to be expected therein. In other words, we have here simply another confirmation of the well-known principle that each problem has to be studied by itself. The uses of the power must be considered, and the territory over which it has to be distributed, and whether one power station is best, or two or three power stations, or any larger number, and whether one voltage or another, or one system of distribution or another, is to be preferred, and how many substations should be installed, are all engineering problems—those are what we are in business to solve. If problems of this character could be settled by rule of thumb many electrical engineers would be out of a job.

I do not wish to be understood in any sense as opposing concentration—I realize the benefits of it but I do not think we ought to accept the deductions of this paper as having as general an application as might readily be inferred unless the limitations are clearly understood.

While it does not exactly bear on the subject of this paper, my friend Mr. Sprague in his opening remarks asked the questions, why did not the New Haven road buy power from the New York Central, instead of building its own power house, and why is the cost of generating current in the New Haven power house higher than it is in the New York Central power house? I can answer the first question at once—the New Haven road tried very earnestly to buy power from the New York Central road but the New York Central quoted 2.5 cents per kw-hr. as its lowest price. It finally said that under some very favorable conditions it might be willing to reduce that price to 2 cents per kw-hr., but beyond that it was absurd to talk of any reduction. It was necessary for the New Haven road to have power at a certain date. It could not wait to conduct long negotiations, to see whether, by bargaining, it could get lower quotations, and it believed it could produce its own power for much less money. That is the reason why the New Haven Road built its own power station.

As to why the cost of generation is higher at the present time, I have no figures before me, but I do know that the New Haven road load factor is very low. The peak demands are high compared with the average consumption of energy. This is a condition which was fully expected, because the electrification which the New Haven road has completed so far is only one step in a general scheme. The New Haven road at the present time is proceeding to extend its electrification from Stamford, 33 miles (53 km.) from New York, to New Haven, 73 miles (117.5 km.) from New York. Further future extensions are probable. It has electrified and will shortly operate the twelve-mile (19.3 km.) six-track branch from Harlem River to New Rochelle over which all its freight passes. The same power house is also soon to supply power to the new road, the New York, Westchester and Boston. The load factor undoubtedly will be much better when these additional loads are put on the station.

Mention has been made of the necessity for providing a sinking fund to amortize the plant cost when a company which has heretofore generated power proposes to abandon its plant and buy power. That point is well taken, but it must of course be remembered that the present demand on any station is an unsafe guide. One of the problems in supplying electric power is not only to get enough power now, but to keep on having enough power hereafter. The load has a habit of increasing, sometimes very rapidly, and that calls for additions to these power houses, and requires additional capital. This fact is often very favorable to concentration. It may well be that the directors of a railroad which has enough power for its present needs may be most reluctant to provide additional capital every few years for power house extensions, and if a large central station company can afford to supply all increased power demands, thus avoiding the necessity for such extensions, the amortization will then be limited to the present investment, while, for increases, the sums that would be reserved for this purpose are available for somebody's profit.

S. D. Sprong: I will refer to just one matter in Mr. Insull's scheme. There are four generating stations in Chicago as shown in Fig. 19, which is hardly a unified system.

W. S. Lee: I rather fear that the membership is drifting into the idea of getting too big units, having only one power station. In my opinion that is not the practise which we should follow in the problem of the centralization of power. The idea of putting everything into enormous units, a little bit larger than anybody else has, and putting it into one spot, will get us all into trouble. Mr. Stott referred to cross-sections of copper being the same, whether it is run from separate stations or from a combination of stations. That is true, but our distances are becoming longer, and that would increase the size of copper. There is no question that the railroad demand in connection with the public utilities, as we usually refer to them, such as street railways and lighting plants, is one that calls for enormous blocks of power, and the demand is likely to be in one spot at one time, and in another spot at a different time. An arrangement is preferable of large stations, or central stations, at different places, and then some interconnection between them, so that in case an excess amount of power is required, one station can assist another.

I am not familiar with railway operation, but that is just exactly what we are doing in the case of power transmission. We are finding that it is an operating problem, and that it is wise not to have our stations too near together, nor to have too great an amount of power in any one spot. We have two power houses quite close together in one case. We have two of our largest plants located on one river in North Carolina, while we operate also on three other rivers, with a total distance of 300 miles (483 km.) apart. We find that these plants in different parts of the territory, with a connection between them, take their load satisfactorily in their respective sections, and further, are able to assist each other in case of trouble. I think centralization of power should not be considered on the basis of enormous stations, grouped in one spot, and everything emanating from these stations, but rather large units in different parts of the territory, each so placed as to carry approximately its own load, and also interconnected to take the shift from one to the other, and assist each other in that way.

Frank J. Sprague: I think the discussion has taken a turn which is hardly justified. I do not understand from Mr. Insull's paper that he recommends concentration in the largest possible station, with the largest possible units, for the power supply of an unlimited district; that would be poor engineering and bad business judgment. With any distribution of power, in any given field, it is perfectly feasible to determine how many stations should be erected, where they should be located and the method by which they should be operated to get the most economical results. Concentration of power in a station should go so far, and only so far, as calls for the use of units of reasonable size, in reasonable number, and with sufficiently diversified service to get a good load factor, and then as the area increases the number of stations should be increased; as Mr. Stott has pointed out, the natural and inevitable result is the interconnection of these stations with each other. Mr. Insull does not hold that all the power stations even in Chicago, or all the power stations in New York or any other place, should be concentrated in a single plant, and I do not believe any engineer would agree with him if he took that stand; in fact his own practise is opposed to this view. Stations should represent such a capacity as will insure a reasonably efficient operation, and cover area enough to provide a proper diversity factor. The gas and electric companies combine loads on the various stations, and must necessarily do so.

The point I do not want to get away from is this: Our object as engineers and members of the Railway Committee, and my desire as the chairman of that committee, is to increase the electrification of railways now operated by steam power. That is not a problem of concentration of antique plants, it is one of the creation of new plants, the taking up of a new problem. I have pointed out the fact that a railway load varies from a few hundred to many thousand kilowatts. With such variations, and the necessities of reserve power, can any engineer hold that railways in the same district should be run by individual central stations? Would any one say that their loads should all be combined in one station because they can be handled by 100,000 kw? I doubt it. But I do say, let there be here a station and there a station, each of them having a sufficiently large capacity to take care of a reasonable load, and then let there be an exchange of power between these stations.

Referring again to the New York Central and the New Haven plants, I was not a party to any question of the selling cost of current in that case. As an engineer, I did recommend that the New York Central should sell, up to the capacity which it could spare, current off its busbars, equally from all phases, to be used in a motor-generator substation. This latter condition was opposed by the New Haven officials.

So far as the cost of power is concerned, perhaps if the New Haven Road had been in the same position as the New York Central it would not have given a central station price exclusive of all other factors, but that does not alter the fact that both stations, Cos Cob and Port Morris, and Yonkers also, could be run for less money if they were under one combined management or ownership, and interconnected where practicable. Take those stations out of the ownership of the railroads, and turn them over to a private corporation which would give a guarantee that it would supply ample power to each of these railway companies, including power for a dozen requirements in the Bronx and all through that section, and they could supply power to both roads for much less than the New Haven power is costing and possibly for something less than the power costs the New York Central.

I noticed that in the Jersey City station, where the load was only 21,000,000 kw. last year, the cost of power is very much less than the New Haven. I do not know why that is so, but I should like to know. There is no such disparity in cost as the relative loads would indicate.

W. S. Murray: As I understand it, there are two matters that are not clear to Mr. Sprague. The first one is the question of the wisdom of the policy of the New Haven in having elected to build a power house of its own, rather than accept the power from a station, already built, adequate in size to take care of our needs. I think that matter was very clearly explained by Mr. Townley. The reason he gave was that we found we could build a power station and supply our own power at a much better rate of cost than the rate we could negotiate with the New York Central and Hudson River Railroad Company, and that was done.

As to the second matter, the cost appearing in the tables that Mr. Sprague has referred to, showing that the rate of generation at the Cos Cob station is higher than the several other stations mentioned, that is quite correct. I have never tried in any way to put a restraint on the presentation of data available in our railway work, but I have rather strenuously objected to the assembling of these data upon a comparative basis, because the conditions of generation at the Cos Cob station are so absolutely different from those involved in the other plants with which these data are compared. However, I yielded to the publication of the data simply because I did not feel that there was anything to be concealed. But I want to straighten out Mr. Sprague on this matter, because I know he has a great deal of confidence in the single-phase system, and I do not want to have him feel that this confidence has been misplaced, as a result of not going fully into an analysis of that situation.

Now the reasons why the costs of the Cos Cob generation are higher than the others are these: First, the Cos Cob station has an extremely poor load factor at present. I think it can be said without doubt that the load factor of the Cos Cob station is the worst in New England. There is nothing that is very disquieting, disturbing or disagreeable about that. The station, of course, has nothing to do with it. No matter what type of station be put there, it would be subject to the same load factor. That load factor exists, and therefore you must credit the station with having a most difficult situation to deal with so far as economical output is concerned. That is the principal reason. Now, it is compared, for instance, with the New York Central station, which has a very low rate of cost of generation, and what is the reason? Simply that there are installed upon that system storage batteries equalizing the generator load throughout the whole day. But we must not lose sight of the fact that while the cost per kw-hr. generated may be lower, the storage battery system requires more kw-hr. generated for 24 hours for a given train schedule than a system not employing storage batteries, such as that, for example, of the New York, New Haven and Hartford single-phase system.

Stated in another way, how much integrated power is required every 24 hours, to operate a certain train schedule? When you have sifted the matter down you find that the number of kilowatt-hours required per train ton-mile propulsion is lower at the Cos Cob station than at any other power station handling heavy electric traction.

Besides that, I want to draw attention to the fact that the

Cos Cob station, when first laid out, was laid out for expansion, and its expansion has now come. These data have been circulating for some time between the companies, and quite rightly, but during this whole period, in which the rates have climbed up, Cos Cob has been upon a construction basis, rather than upon an operation basis. Take a station that has the end of it knocked out, and a new extension, of more than 100 per cent, being added to it, furnishing steam to the contracting plants surrounding it, and its main turbines operating many times on a non-condensing basis, naturally if all this power is not represented in the divisor the rate must be high.

These are some of the reasons which show that the rate must be higher. If you come to me a year from now, in June, 1913, I can tell you another story. I will not have storage batteries installed in the plant, they never will be necessary, but in the place of these storage batteries there will come a different kind of means to bring a very even and more efficient load. In the valleys of our present load will be placed a magnificent freight load changing our very peaked condition of load curve and producing an excellent load factor. Besides that, all of the power that is to be generated at the Cos Cob station is not to go to train propulsion, but some of it is to go to the trolley roads and the lighting companies which the New Haven company owns. This explains in a way my demurrer to having these tables circulated, simply because they do not show the final results.

It is exactly the same way with the construction. In about a year's time, when the New Haven road can say it has under wire 550 miles (885 km.) of track, and has a complete division running by electricity, which is not in any way associated with steam, and every wheel west of New Haven is turning by electricity, when that time comes valuable data will indeed be at hand.

William B. Jackson: I feel that this discussion of steam railroad electrification is extremely desirable in connection with the paper under consideration, and I feel that Mr. Insull's analysis has brought out clearly the factors controlling the situation, for we have right here, in the case of the New Haven road, an instance of a plant taking care of a certain kind of service wherein the costs run high, and we must all admit it, from what Mr. Murray tells us. The plant will eventually take on different kinds of service which, in this case, will have an extra large diversity factor, and eventually bring his plant to be one of the best, so far as the diversity factor is concerned, and, let us hope, so far as the cost of production of power is concerned.

It is an interesting fact that a person is prone, in the consideration of a paper, to be influenced by the title, but in this case the title is likely to carry him far afield, because here the case of the electrification of steam railroads is an important factor only as it adds to the power plant, enabling the power plant to cover large areas, or to supply all of the service in large areas, and to supply additional power which will improve the load factor and thereby improve the cost of generating the power. The alternative title that Mr. Insull suggests for his paper, " The Generation and Primary Distribution of Energy for Given Areas," is a big subject, a magnificent subject, and includes as one important factor this matter of electrification of steam railroads, as one of the services. We must also appreciate and have it clearly in mind that there is no suggestion of concentration of power in great power houses, for the reason that even though we follow out the suggestions which the paper contains, we will never concentrate in one power house more than can be economically carried by that power house. The paper is a splendid plea for the concentration of all electric service for any district which may be economically supplied from a single power house in the one power house, thereby securing the advantages of obviating the need for duplicate transmission lines and duplicate substations, and taking advantage of the improved load factor which Mr. Murray has pointed out to us in the reduction of the cost of electric power. Nobody, I believe, can take exception to that general principle, that if we are to provide power economically in this country we must get rid of the conditions where two or three different generators, parallel generators, are supplying the same sort of power.

We must also go further. In thinking of this paper, we are prone to think of it as applying merely to such great centers as the city of New York, Boston and outlying territory, and Chicago and its outlying territory, but we must recollect that the considerations in this paper take into account just as clearly the conditions around the smaller centers where, by bringing together into a single power plant all services of energy which are now or shall be later supplied by electricity, we are likely to get very important advantages, from the standpoint of less cost per kw. of construction of plant, and less cost per kw-hr. of output of the plant, and a tremendous improvement that is possible in the matter of general management and the other general expenses, which must take into account the physical operation of the plant, the policies which are to guide the service of the electric power in the districts under consideration.

We must also go a step further and appreciate that if we are to follow out logically the plea of this paper we must not only have these plants properly located and of proper size to carry all of their power, all of the electric power in their districts, but we should also have them so located and interconnected that satisfactory correlation is possible between the operations of the several plants, whereby there are undoubted gains to be obtained.

Lee H. Parker: I have already stated publicly that I believe all of the power required for the transportation facilities in Boston and its vicinity could be furnished by one large company. I believe that the steam roads within the Metropolitan District, when electrified, might have their power supplied, either by the present Boston Elevated Railway Company, or some other large transportation company, which in turn could be amalgamated with the existing power and lighting company. I cannot see any good reason why the comparatively small amount of power required for the electrified steam roads should not be successfully and economically handled by any one of the large power producing companies in existence here in Boston today.

C. O. Mailloux: As engineers we must appreciate the fact that circumstances alter cases. Guided by that principle, one would see, offhand, that it would make a great deal of difference what the circumstances were in determining what the decision must be. There are certain fundamental principles which serve to guide the engineer when he looks at things from an economic, and also, perhaps, from a financial point of view. From the standpoint of the conservation of energy, and of capital, and of everything else (which is one of the live questions of the present day) it is far better that we should specialize—that the one who is producing electrical energy should produce electrical energy only, and sell it, and produce all that he can, while the man who is producing " transportation," or who is dealing with the " railroad-economy " side of the problem, should confine himself to that. But here, again, circumstances may alter cases. There are many cases where it would be far better that they should be combined, and there are great advantages, intrinsically, in doing that.

In connection with the development or new electrification of a traction enterprise, it would certainly be, in many cases, very useful and very convenient if one could detach the production of power from its utilization. Take, for instance, a project involving $10,000,000. If it is based upon the production of electrical energy by the company that is going to develop the project, one must include, in the cost of equipment, from $1,000,000 to $2,000,000 or $2,500,000 for the generating plant. Hence, in a case like that, if power can be procured from an existing power station a project can do away with a certain amount of financial handicap, from the very fact that it is able to get along with less capital at the start. We all know that the new project finds it hard to enlist capital; it finds it difficult to show a return on the proposed investment; but, even if it can show a return on the whole investment, the problem of financial feasibility and realization is greatly simplified if the total amount of capital asked for is reduced, say, 15 to 25 per cent.

In a case like that, therefore, the possibility of deriving the requisite supply of electrical energy from a central source of supply, such as is contemplated and advocated in the paper of Mr. Insull, may be of great value. In the first place, it would obviate the necessity of capital being invested in two, three or more " lumps " for the generation of energy; which means higher efficiency in the production of energy, also lower cost and lower managing expenses. These are centralized and correspondingly reduced, and from the standpoint of the man who is interested in the purely transportation aspect of the problem, it simplifies the problem, because it necessitates his raising less capital and undertaking less financial and other responsibility.

One can see that the man who is interested in a new project, if he can buy power, can afford to pay, not only what it would cost him to produce it, but just a little bit more, in other words, he can afford to some extent to capitalize a part of that responsibility or a part of the difficulties which he would experience and would need to overcome in producing and procuring the necessary capital himself for the erection of a power plant and the production of the power. Hence, admitting that he were able to produce and procure the capital, if he can avoid the necessity of it, it is somewhat to his advantage to do so; and he can afford to pay a little more for it. However, as already stated, circumstances alter cases. The preceding reasoning is not always true. Take projects which are financed by large concerns, which are able to raise any amount of capital that is required—they find it just as much to their interest to employ capital, and keep it active, and make a return on it, for electric lighting or for power, as for transportation. In a case of that kind, therefore, the possibility of buying power is not of so much interest; but in the case of smaller projects, it is generally a factor of the greatest importance.

As these smaller projects grow and develop and extend, a time is reached in their career when most of them would find it to their own interest to produce their own power, and fortunately, when they have reached that stage they have " made good," so to speak—they have demonstrated their usefulness and have obtained from the public their " certificates of public utility and convenience;" and they are then able to enlist capital on much better terms and to much better advantage than they would have been in the first place. There are both of these classes of projects, and one general solution will not fit both classes.

It is a very instructive and useful thing, however, for this Institute to have had placed before it so clearly and effectively the possibility of the supply of power over large areas and over large districts from one centralized source. We must, of course, understand that in using the term " centralized " we do not necessarily restrict ourselves to *one* station. No one, in the case of a very large district, or a district in which the density of services and the total amount of current consumed was very great, would consider " putting all his eggs in one basket." It would be very much better to take a certain maximum size of plant, and to build two or three or more of them, connect them together, and use them in such a way as to obtain the best result, including a certain factor of insurance against breakdown.

I wish to emphasize the fact that there is a great advantage, to those who are interested in the newer problems in which public utilities in the form of transportation and lighting are concerned, to have placed before them the possibility of studying the modern conditions of the supply of electrical energy, without being compelled, at least at the start, to go into the business of producing that supply themselves. It is a great thing to be able to specialize, and to find that some one else is specializing in a way that enables you to benefit by what he is doing and to save yourself some trouble and some expense.

P. W. Sothman: The whole question as presented in this paper is of universal importance, and is, at the same time, a question which cannot be dealt with by means of any fixed rules. I believe that the conditions of each problem will furnish us with certain guides, which will enable us to do the best thing that can be done in that particular case. As an illustration of the present subject, it was thought for some time that power plants should be concentrated as much as possible, and even placed under one roof; but it is my opinion that we can go very much too far in that direction. Experience with several accidents in recent years has shown that it is not the best policy to put too many eggs in one basket, and I do not believe that we shall ever be able to use a general rule which will tell us to do a certain thing in any particular way without involving a study of the project from beginning to end, and from all points of view, that is, from the commercial side as well as from the engineering side. Unless we can make such a thorough and independent examination we are not practising engineering at all, but are still the tools of the financier or the banker, or of some commercial interests which are using us for the purpose of filling their pocketbooks.

We must be stiff-necked and say: " The engineering problem of your system or in connection with your project is so and so," regardless of the fact that the satisfactory solution of the engineering problems does not necessarily warrant an equally fortunate commercial possibility, in which case engineers of today are only too often turned down by their financier with the comment, " That engineer is no good. I will have to get another one."

In my opinion great advantages can be obtained, and have been obtained, in the consolidation of railway loads with commercial loads. The load factor of a certain railway near Toronto, which we connected up just a year and a half ago, was a very poor one. The load diagrams of this railway were studied at some length, and we started in to help the company a little by cutting out certain trains at certain hours. The trains cut out were mostly freight trains, and these were handled during the night time to a great extent, but a small freight service was arranged to fill out the gaps during certain periods of the day.

The success of this move was somewhat surprising. The railroad was, previously, taking an average load of from 850 to 900 h.p., with peaks running up to 1700 h.p., and because of the educational work we were able to do, effecting a readjustment of the freight train schedule, and otherwise telling the company where its practise was not right, and how to improve it, the maximum peaks, I believe, do not now exceed 1200 to 1300 h.p. I am a believer in education, which, if coupled with fairness, can accomplish very much. If two men get together they can always thresh out something, and if both have a disposition to be fair and to meet on mutual compromises they can generally achieve good results.

In Europe the distribution of power for railway and commercial uses has been done largely in the last few years by the use of storage batteries. When I was over there last year I was very much surprised to see that a number of power stations had succeeded in almost entirely eliminating their peak load, that is, the curve of consumption was kept as straight as possible. This is a condition which has not yet been attained to any great extent in America. I have found that in order to accomplish this, different kinds of mixed systems are used abroad—sometimes the cars carry storage batteries which supply the load at certain periods, and sometimes one finds second trolley wires which are used for direct current in times of emergency, all of which gives a good flexibility.

I must admit that such installations would not receive approval the first time they were presented to a company in this country, but when you figure out the whole scheme, based on continuous service, or, in other words, when you figure out the real value of absolutely continuous service, the cost of generation, which is only a part of the whole, will fall down reasonably low, and should convince your customers of its desirability. There is no question but that continuity of service is one of the leading factors in the supply of electric current.

I feel that the question of the electrification of steam railroads is 99 per cent a commercial one. As to the engineering phase of the question, there is no doubt that it can be successfully done, but, as stated above, we must study each case on its own merits, and see the light as distinguished from the shadow.

C. L. de Muralt: Mr. Townley made a certain *reductio ad absurdum* when he showed that, if you can use a single power station to supply one town, there is no reason why you should not use it to supply one county, or one state, or finally you might as well supply all of the United States from one single power station in Chicago. That, of course, would be absurd, but I think it is not quite fair to Mr. Insull to consider his paper in just this manner. I do not think Mr. Insull had any such thing in mind, but I can easily conceive of his having in mind the supplying of all of the United States from one single network of lines, controlled by one company, which owns all sorts of power stations in the most convenient places, steam, hydraulic, etc., and I do not doubt for one moment that the country would benefit by such a combination, provided it could be properly regulated. The figures which Mr. Stott has given show plainly how such a combination of various loads will decrease the operating expenses proper, and then there is the still greater gain in the saving of fixed charges on equipment which can be eliminated if the load factor is high.

On this point it seems to me worth while to call attention to some information contained in Mr. Insull's curves but not specifically mentioned by him. I will first refer to Fig. 4, which represents the power requirements of the railroads electrified in the district of New York, the Pennsylvania Railroad, the New York Central and Hudson River Railroad and the New York, New Haven and Hartford Railroad. You will notice that each one has a strong peak at about eight o'clock in the morning and another strong peak at about six o'clock in the evening, and a very deep valley between. Incidentally you will notice that the peak and the valley are much less in the curve of the New Haven than they are in the curves of the Pennsylvania and the New York Central, which seems to contradict Mr. Murray's claim that his company has the worst load factor.

What I wish to bring out, however, is that the two peaks of this kind of railroad service practically coincide with the customary peaks in the lighting and power business, which also occur roughly at from six to eight o'clock in the morning and from six to seven o'clock in the evening. In other words, superimposing this sort of a railroad load on the usual power and lighting load will not help very much, which may explain why Mr. Insull is disappointed in the saving which he can make by improving the diversity factor in this manner. It is necessary to remember that these are all strictly suburban train services. The New York Central, the Pennsylvania and the present New Haven installations run essentially suburban passenger trains.

Now let us refer to Fig. 8. You will see at once the difference between the passenger curve and the freight curve. The passenger curve in this case also represents a suburban passenger train service. It stands for the Chicago terminal operation, and it has two very plain peaks, but the freight curve is a very much smoother curve—as a matter of fact, it is practically at its maximum value just during the time when the other curve has its deepest valleys. Thus, while the total is not by any means a horizontal line, the difference between its lowest point and its peak is very much less than in the case of the passenger curve.

The conclusion which I should like to put before you is this: The electrification of our railway terminals alone is not going to help us very much, but the further out we go, and the more we include freight business and through passenger trains, the more will we be able to smooth out the load curve. This is perhaps the strongest argument which Mr. Insull has brought out in his paper in favor of consolidation over as large a district as possible. We need not necessarily consider a single power house in one city, but let one company furnish, by means of a series of power houses and a network of lines, the electric energy required for all purposes, light, power and traction, in a large territory, and the cost of electricity to everybody concerned is bound to be reduced.

N. W. Storer: Apparently all of those who have discussed Mr. Insull's paper are agreed on certain things. Certainly no one can refuse to admit that, from an economic standpoint. it would be better if all of the power used in any community were generated and distributed by one organization, provided that organization was so managed as to give the service desired by power users. Looking at it broadly, without any reference to organization, if every power user were able to get as much power as he desired at any time and in any place by connecting to a power distribution system, he would be relieved of all responsibility of a power house and everything connected with it. Under such conditions a great many projects would be financed, that are now impossible. It should be possible, as Mr. Insull states, for power to be distributed in this way and sold at a lower cost than it would be possible for the individual users to generate it. This statement, I believe, will be admitted by all.

When it comes to the organization of the distributing system, of course it would naturally follow that generating stations should be of the most economical size, and should be so interconnected as to get the best and most economical distribution system. It might be most economical to have one organization to distribute power to the entire country. This, of course, is not a possibility at the present time, neither is the single distributing company in large cities a possibility, for the reason that no large railway corporation or other large user of power is going to put this work in the hands of any company which may be controlled by rival capitalists. If there were no fears on the part of power users that they were putting their business in jeopardy by permitting all power to be concentrated by one company, there is not a particle of doubt in my mind that concentration would be made in the near future. There are too many cases in view at the present time, where communities are at the mercy of a single corporation, being obliged to pay exorbitant rates for their power, to encourage people to extend this system any further. The ideal system which Mr. Insull advocates can be put into effect only when the power companies are put under the control and the prices are subject to the regulation of an honest and efficient government. The question then, resolves itself into one of politics rather than engineering.

Now, as far as the railway load itself is concerned, it has been pretty clearly demonstrated that the railway load will have the best load factor of any of them. The passenger system alone has very bad peaks in its loads, but when a freight load is superimposed on the passenger load, such as will be the case in any large city where there is a great deal of shifting and freight handling going on all the time, an exceptionally good load factor is obtained. From this standpoint, then, there would be little advantage to the railroad in buying power from a central company. Railroad companies can generate their own power, but, of course, one railway company will not be able to sell power to a rival railway company. If a number of railways are to be operated by power from a single power system, this system must be under joint control of all the companies concerned, or controlled by a company which is absolutely independent of any of the others, and is bound to treat all companies alike.

In further consideration of the application of this paper to steam railway electrification, I do not feel that it is going to be necessary for the railway companies to use absolutely the same system of distribution as is in use in the majority of the central stations in any given locality. It certainly would be advantageous if railways could use this same system, but the railway load is big enough and the load factor is good enough to give the most economical production of power, and if the railway companies found it more economical to adopt a different system of distribution than the one in use locally, they would be entirely justified in changing. That, of course, simply means that if they wished to do so, they could adopt a different frequency—in other words, if 15-cycle alternating current with either single-phase or three-phase distribution to railways were found in the long run to be the best suited for their operation, they could be perfectly free to adopt that frequency regardless of the frequency in use by other central stations. I do not wish to be understood as stating, or necessarily believing, that 15-cycle current is going to be the one adopted for the electrification of steam railways. My statement is not intended to have any meaning between the lines. The frequency of 15 cycles is given simply as an example.

Edward N. Lake: Concerning the Boston Elevated Railway Company's new power station, about which Mr. Insull had something to say, I wish that I were at liberty to give some figures on this question, but perhaps all that need be said, now, is that considering the rate which I understand was offered by the Edison Company, and the actual cost now being secured by the new station of the Boston Elevated Railway Company, the directors of the latter company have had no reason to question the wisdom of their decision to build their own power station.

Frank J. Sprague: We have in use three systems of electrification of steam railroads, somewhat distinctive: polyphase, single-phase and direct-current, and some combinations of two or more of these. I am somewhat of an agnostic, but I have directed my energies for some years past not only to promoting electric railway operation, but to trying to see that efforts should be consistently carried forward in each of these fields to arrive at the normal maximum development of the apparatus which goes to make up the constituent part of each of these systems. We have arrived at a reasonable degree of satisfactory operation so far as central station equipment and apparatus is concerned; we have gone nearly as far as we can hope to go in the matter of reliability, in the matter of efficiency and in the matter of producing units of economical size. We have arrived at certain general conclusions as to the operation of central stations. We have also learned the necessity of permanence of construction, when we deal with steam lines which have been electrified—where we are tending all the while to more exclusive rights-of-way, where highways shall not cross railroads at the same level. We are also introducing, from time to time, important improvements in the matter of physical construction. We are adopting certain standards in the interests of our great cities, and our public service commissions are placing more and more restrictive obligations upon those who supply electricity for use within crowded areas.

In the matter of line construction, whether for transmission or for carrying the overhead wires over a railway, or the construction for protected or unprotected third rails along the right-of-way, we have arrived at fairly definite conclusions, and fairly good experience in the matter of cost. In the matter of motors there have been very great advances made in the past three years, so that I think we can look forward with reasonable assurance to certain normal limits to the potentials which are practically available for each of these systems. I do not mean that higher potentials are not workable, but there are limiting features which come up which go to make up a balance which we must regard.

In polyphase work we should not go above 6000 volts between adjacent trolley lines, because when we go above that we do not gain enough in the matter of economy of transmission to pay for the extra cost of maintaining these wires at this excess of difference of potential. For single-phase lines I doubt if we will achieve anything of importance by increasing the potential much above 11,000 to 12,000 volts, possibly sometimes to 15,000 volts. In direct-current work the old standard of 600 volts has disappeared, and my impression is that where overhead lines are used there is a practical, normal limit, all things considered, of say from 2500 to 3000 volts. Where protected third rails are used, there is a normal limitation of from 1200 to 1500 volts.

So far as the motors themselves are concerned, we have got pretty nearly to the limit of capacity measured by weight, with and without ventilation, natural in the motor or supplied from an extraneous source.

Now having arrived practically at these limitations, I say that the time is fast approaching when, as engineers—divesting ourselves of any particular pet notions, so far as it lies in our power, and not abating in any sense the right to make individual efforts along the lines of progress for which we are responsible—we should pave the way to get comparative results which will enable us to arrive at proper conclusions in the future. In and around New York we have the New York Central, the premier system so far as that particular class of work is concerned, and we have the New Haven system, one of these operating to North White Plains and Yonkers, and in the future going on also to Croton and possibly to Poughkeepsie, and the other operating at the present time to Stamford, and later going on to New Haven, and perhaps further points. Each performs a service which is adequate so far as the hauling of trains is concerned, but one which is disappointing in some ways so far as the total economic results are concerned, for in each case the railroad is, for the present, handicapped by having to operate in the same zone with steam equipment, and also because all the wheels of those divisions are not turned electrically, as I have, for the past seven years, urged should be done.

A sub-committee of the Railway Committee has been charged with the duty of suggesting methods for promoting the use of uniform reports by the steam railways which have been electrified, covering the electrified divisions. I think it is the duty of all electrical engineers to promote, as far as lies in their power, these uniform reports. The five or six railway central stations have already framed up these for their individual comparisons, but I think probably we would get a little further along than we have done if these reports would also deal with the general equipment. and specifically with the cost of operation. The latter will not always show up well for any one of these systems, and in other respects it will show up very well. Now, when a single-phase system, or a direct-current system, or a polyphase system, is extended over an area sufficient to eliminate the steam engine within the zone of operation, and when those who are in executive control and in responsible charge are willing to lay down in a comparative manner all the facts about their equipment and operation, I think that the electrical engineers of this Institute will have that to which they are entitled, and which eventually they must have before they can come to any final conclusions, irrespective of my own or any other man's impressions, as to what should be done in the future. So far as lies in my power as a member of this Institute, that is precisely the thing I am going to work for—to get the facts, no matter what they are, about any and all systems, so that we can all pass proper judgment and arrive at correct conclusions.

I cannot agree with some of the conclusions expressed in the paper, because I have not sufficient data, but there is underlying all this discussion one fundamental fact. Everyone is agreed that we should have consolidation of power houses sufficiently large and well enough equipped to insure reliability and safety in operation and economy of operation. Within a given area a station should be capable of supplying all the energy required in that area, and two or more of these stations can properly be connected together for the supplying of larger areas; in other words, we can extend the high-tension busbar over large areas, and where there is a common territory between two stations either can be utilized to relieve otherwise unbalanced overloads.

I am in hopes of being instrumental in trying to bring about the state of affairs which Mr. Sothman happily voiced, that where two or more people who have all of the facts, and have that one quality which is the highest quality engineers can have, and which all engineers should possess to a greater or less degree, the power to analyze, these men cannot help arriving at a unity of judgment provided they are fair-minded in their engineering notions.

A paper presented at the Philadelphia Section Meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., April 8, 1912.

SOME FEATURES OF THE OUTDOOR ELECTRICAL INSTALLATION

BY F. C. GREEN

Economy in the construction and operation of power systems is engaging the best thought of engineers with the purpose of making the systems attractive to investors, as well as to those who utilize the power. The outdoor installation is based principally on economy in construction and partly on economy in operation.

The presentation of a previous paper[1] on this subject was the occasion of much discussion by eminent engineers. Many of the details of construction and operation were gone into. The idea was indorsed by some and opposed by others, while in the main the discussion was mildly favorable. It was generally agreed that the principal consideration is economy. Some careful figures made for small substations show a net saving of 10 to 30 per cent over the indoor installation. At that time the outdoor installation was limited to transformers of small capacity except some 500 kv-a. 60,000-volt transformers that had just been installed. According to the general opinion expressed, the principal difficulty was to prevent moisture from getting into the outdoor transformers and switches. The extra cost of making them water-proof and air-proof was estimated to be from 6 per cent to 8 per cent. There was some difference of opinion as to whether life and property hazard, and convenience of operation would be seriously different from these features of indoor stations. Most of the discussion was based

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[1] *High-Voltage Transformers and Protective and Controlling Apparatus for Outdoor Installation*, by K. C. Randall, TRANSACTIONS A. I. E. E. 1909, XXVIII, I, page 189.

upon more or less apparently well grounded opinion, practically no experience being given.

List of Transformers. Following are the ratings of some transformers built for outdoor operation, since the presentation and discussion of the 1909 paper:

LOCATION	NO.	RATING
North Carolina.......	3	60–140–22,000
New York............	1	60–150–16,500
North Carolina.......	3	60–300–18,480
Pennsylvania.........	4	60–150–33,000Y
North Carolina.......	3	60–150–22,000
Minnesota...........	1	60–150–66,000
Minnesota...........	6	60–200–33,000
North Carolina.......	3	60–200–22,000
North Carolina.......	3	60–200–44,000
North Carolina.......	3	60–500–50,000
North Carolina.......	3	60–500–22,000
California............	3	60–200–66,000
Tennessee............	3	60–200–66,000Y
California............	3	60–300–66,000
Alabama.............	3	60–300–66,000
Montana.............	2	60–200–50,000
Montana.............	1	60–200–50,000
North Carolina.......	4	60–2750–100,000
Georgia..............	6	60–3333–110,000
Georgia..............	9	60–1000–110,000
Florida..............	3	60– 667– 62,400
Florida..............	7	60– 500– 33,000

In numerous transmission systems, high-tension oil switches and lightning arresters are installed outside. In several substations, transformers, as well as high-tension and low tension-buses, are outdoors.

Types of Indoor Construction

Thus we find the extensiveness with which the idea is being put into practise, warrants further consideration of the advantages and disadvantages involved. A study of the principal factors of economy seems to lead to the conclusion that a greater percentage of saving may be expected than the values given in the previous paper and its discussion; and that the idea may be profitably extended to the installation of oil switches, buses and transformers outdoors for both substations and power stations,

PLATE II
A. I. E. E.
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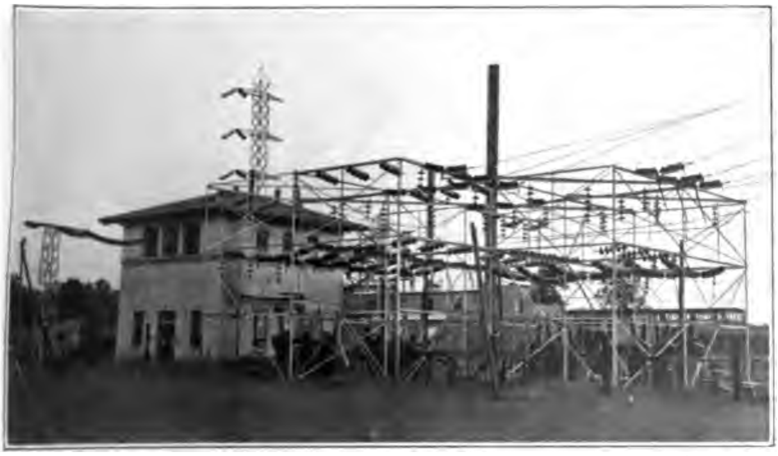
[GREEN]

Fig. 1—Showing Construction of Generator Bus Compartments

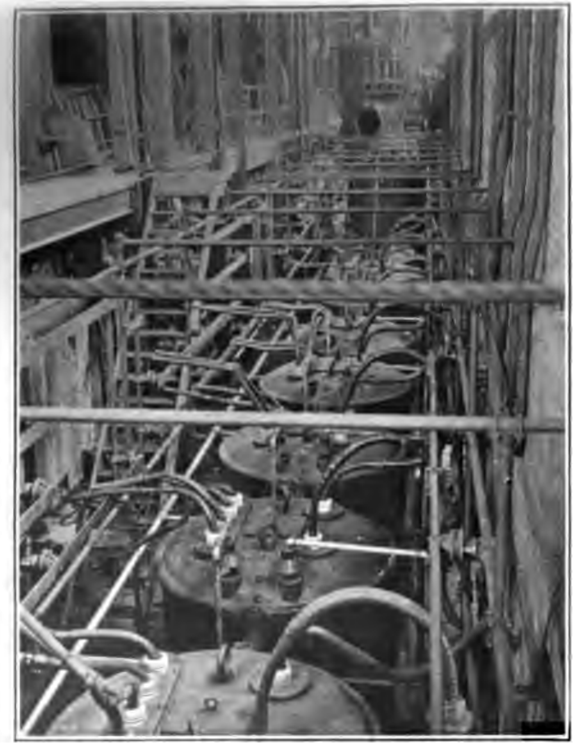


[GREEN]

Fig. 2—Outdoor Installation of Oil Switches and Buses for 100,000-Volt Service

[GREEN]
FIG. 3—OUTDOOR INSTALLATION OF 100,000-VOLT TRANSFORMERS

[GREEN]
FIG. 4—OUTDOOR INSTALLATION OF 100,000-VOLT TRANSFORMERS



[GREEN]

FIG. 5—OPEN TYPE OF TRANSFORMER INSTALLATION IN CLOSE QUARTERS

[GREEN]

FIG. 6—OPEN TYPE OF INSTALLATION—100,000-VOLT BUSES AND SWITCHES

PLATE V
A. I. E. E.
VOL. XXXI, 1912

[GREEN]

FIG. 7—COMPARTMENT TYPE OF INSTALLATION—GENERATOR BUS COMPARTMENTS

[GREEN]

FIG. 8—COMPARTMENT TYPE OF INSTALLATION—HIGH-VOLTAGE BUS COMPARTMENTS

excepting those where conditions make it imperative to have them indoors. It is believed that a review of the existing conditions as embodied in the whole practice of generating, transmitting and distributing electrical power, will prove more valuable in arriving at correct conclusions than the making of detail estimates for the requirements of any given and limited application of the idea.

As related to the subject, there are two general types of housing construction for electrical apparatus; the open housing and the compartment housing. The open housing type includes those stations where most or all the apparatus and buses are not installed in individual compartments, but in open spaces. The compartment housing type includes those where most or all of the apparatus and buses are installed in individual compartments. In existing installations the two types of housing are pretty well balanced.

In the compartment power station, approximately 60 per cent of the ground space is required for transformers, buses, switches and lightning arresters. From mere observation of these plants it can be seen that the cost of the compartment construction is at least equal that of the housing including the foundation, for the apparatus and buses specified. Also the substantial construction used in many of these buildings must result in a very considerable percentage of the cost of the apparatus and buses being consumed in the cost of the portion of the building and compartments occupied by them; and this percentage represents a considerable percentage of the cost of the whole plant. The amount of saving effected would be greatest in the compartment type of station. In the open type of station, the saving would decrease from those having part of the apparatus and buses enclosed, to a minimum with those having only the outside walls.

OUTSIDE INSTALLATION AT GENERATING STATION

It frequently happens that the location of hydroelectric power houses necessitates large expenditures for building foundations. The outdoor installation admits of using any convenient space nearby and would effect considerable saving above the amount estimated for more favorable locations.

THE OUTDOOR SUBSTATION

The substation repair house would serve as panel room for control switches, in case the substation was of sufficient size to warrant having a repair house. Where substations are used for supplying mills they may be located sufficiently close to the mills to make it unnecessary to have a special repair house and operating room. Part of the mill building may be used for these purposes. Electrical railway stations require sufficient housing for the revolving apparatus and control panels. Also there should be sufficient room in the building to have a transformer repaired. For very small repair houses arrangements can be made just outside of the house for taking the transformer out of the tank, in order to avoid so much head room inside. This is a common practice with at least one large power company, which has a great number of indoor substations. A simple wood or steel structure is erected just outside of the station. A device for lifting is provided, and it may be transported from one substation to another.

Where the substation embodies much apparatus it is advisable to provide ample facilities for shifting the apparatus around. For instance, if a transformer should fail the facilities ought to be sufficient to admit of its being readily transported to the repair house, and if necessary, another transformer moved into its place. Tracks should be laid so that any transformer in the installation can be readily transferred from its operating position to the repair house, by means of a truck. For small substations where a repair house is provided, it can be located close to the transformer installation. Heavy timbers may be used for a track on which to roll the transformer. In fact, except for the very largest sizes, transformers can be more easily handled with pipe rollers on timbers than with the elaborate wheel construction and the necessary rails.

MOISTURE

We now come to those features of the details of apparatus upon which the whole question of the success or failure of the outdoor installation depends. In the previous paper and its discussion, it was quite clearly brought out that the most vital question is whether transformers, switches and lightning arresters can be built so as to be weather-proof. Since a considerable amount of this apparatus is already operating out of doors, it is only a question of the elapse of sufficient time to prove failure or success. Experience with small transformers that have been located on poles, indicates that there is not as much danger from moisture as is feared by those who have discussed this feature. Out of 74 transformers, 1 to 25 kv-a. in size, that had been in service two to five years, near the seashore, where the moisture conditions are considered unusually severe, samples of oil were drawn and tested. The puncture voltage obtained between ½-in. copper disks, 0.2 in. apart, ranged between 25,000 volts and 44,000 volts. These values do not show that any moisture got into the oil, notwithstanding that many of the transformers were idle during a considerable period of each winter. Transformers used for pole suspension have never been made air tight, most of them in fact being provided with a breathing space in the gasket between the cover and tank.

On the other hand, practise has shown that in some instances, indoor installations are subject to atmospheric conditions that admit very serious condensation, inside of the transformer cover. In those instances where serious condensation has taken place, no special provision was made either to make the cover air tight or to give it a breathing space. Thus we find that practise seems to show a paradox as far as opinions that have been given are concerned, but, if a careful analysis is made of the conditions involved, the facts are not so surprising.

The weight of water per cubic foot of air is nearly always greater in buildings than outdoors, except during periods of rain. This statement is based upon the facts that temperatures inside of buildings are higher, which admits of the air carrying more moisture; buildings are occupied by people whose breathing tends to increase the humidity; water may be exposed in the buildings in such a way as to increase the humidity. Transformer stations are rarely specially heated, with a view to making them comfortable; still as a rule they are kept at a higher temperature than the outdoors. In such stations, and in transformers that are not especially ventilated or especially tight, changes in temperature conditions are not followed by an immediate readjustment of pressure conditions. That is, the air in the station and in the top of the transformer, having no free and easy path to follow, will assume the temperature change without immediately assuming the corresponding pressure change; which condition, in case the temperature is lowered, results in condensation, especially considering that the enclosed air is liable to have more water per cu. ft. than the outside air. With the transformer out of doors, and with proper breathing space so arranged that neither mist nor rain can get inside, the atmospheric conditions are free to assume immediately any change in temperature or pressure in the air outside. It seems, therefore, safe to conclude that there is little chance of condensation inside the top of a transformer located out of doors, and with a protected breathing path provided.

TABLE I

Pounds of water necessary to saturate 1310 lb. (594.206 kg.) of air (18,000 cu. ft. at 25 deg. cent.) at various temperatures; atmospheric pressure.

Degrees cent.	Pounds Water	Kilograms
22.2	23	10.4
27.7	32	14.5
33.3	44	19.9
38.9	61	27.6
44.4	84	38.1
50.0	115	52.1
55.5	158	71.6
61.1	217	98.4
66.6	302	136.9
72.1	426	193.2
77.7	622	282.1
88.8	1650	748.4
94.3	3760	1705.5

However, if a more extensive practise should disclose that condensation is found occasionally, the most satisfactory means of preventing this would seem to be the introduction of a very small heating coil in the top of the transformer; a free breathing path still being retained. A lining of heat insulating material on the inside surface of the cover, would tend to retain the heat and to prevent condensation. A very slight increase in the temperature of the air in the top of the transformer will have the desired effect. The attachment of drying breathers to the transformer is unsatisfactory in several respects. The material used for drying the air tends to throttle the circulation and free exchange. The care required in keeping the breathers in good condition is objectionable. They are cumbersome. To make tanks air tight is difficult and expensive. Unless they are absolutely tight the condition inside the top of the transformer will be favorable for condensation. The same facts and reasoning advanced in connection with the transformers, apply for the construction of lightning arresters, and oil switches.

DIRECT HEAT FROM THE SUN

The prevention of the transformer's absorbing the heat from the sun in the summer time is a problem easily solved. By placing around each transformer a cylinder of some simple heat insulating material which may be inappreciable in expense, we not only get rid of the heat from the rays of the sun, but slightly increase the cooling, due to the chimney effect. It has been found that sheet metal, with the surface next to the apparatus, painted white, makes an effective screen.

TYPES OF TRANSFORMERS FOR OUTDOOR INSTALLATIONS

Air-Blast Transformers. Air blast transformers can easily be adapted for outdoor operation. The intake of the blower and the space where the air is discharged from the transformer can be so constructed, with little additional cost, as to prevent the entrance of rain into the windings. There is no question of the effects of the direct heat of the sun or of freezing. Moreover, assuming that a small amount of rain should be drawn in through the blower, the effect would not be serious; the higher temperature of the air would give it so much greater capacity for moisture that the rain would be absorbed by the air and carried away. (See Table I).

Water-Cooled Transformers. In the use of water-cooled transformers provision must be made for preventing the freezing of the water in the circulating piping and in the cooling coil. The cooling coil should have its terminals brought out at the bottom of the transformer and the piping either run under ground to the sources of supply and drainage, or heavily lagged if the piping is run above the ground. The piping should be so laid that it can be drained when it is not necessary to circulate the water. The critical situation as regards freezing occurs when the transformer is held idle. These occasions rarely exist, except where a spare is held. In order to take care of an emergency, space for an electric heating coil can be provided under each transformer, in order that the coil may be put in position when necessary.

Oil-Cooled Transformers. What will probably prove the most satisfactory type of transformer for outdoor operation is the oil-cooled type, which requires no auxiliary cooling apparatus, and the least attention in service. By means of the cylinder placed around the transformer to shield it from the direct heat of the sun, the natural circulation of the air is slightly increased. There is ample supply of fresh air. In discussing this subject it may be well to refer to the use of large, self-cooled, units for indoor stations. A number of such units are now in service but have not operated sufficiently long to determine the vital question of heat under the conditions. Judging from the little attention that has been given to ventilating stations where oil-cooled transformers are installed, and from the temperatures that have resulted, it will not be surprising to find that the very large units cause the temperature of the buildings in which they are installed to become dangerously high. Assuming the installation of three 2000-kv-a. units in a building of the usual construction and size, we find that under full load approximately 120 kw. of energy must be dissipated. Twenty-two thousand cubic feet (623 cu. m.) of air per minute would have its temperature raised ten degrees by this amount of energy; or, a building approximately 40 ft. by 20 ft. by 27 ft. (12.2 by 6.1 by 8.2 m.) high would require having its air entirely renewed once every minute in order to prevent a rise greater than 10 deg. cent. in the room temperature. In order to prevent undue station temperatures it is necessary either to have artificial circulation of the air through the building, or to have the building unusually well ventilated.

Prevention of the freezing of the oil in case a transformer should be held out of service, can be effected by means of an electric heating coil placed beneath the transformer. However, experience has shown that there is no particular danger in the freezing of oil; also certain grades of transformer oil do not freeze at temperatures as low as minus 40 deg. cent.

INSTALLING

Installing high voltage transformers involves considerable expense and time. Where they are shipped with oil in them, the operation of installing is reduced merely to placing the transformer in position and connecting in circuit. This procedure has the disadvantage that the transformers are more difficult to handle, and according to the practise that has been followed, no inspection is made of the internal parts to determine whether they have been disarranged in shipment. Therefore, for the present at least, the great majority of transformers must be put through a drying process.

There are three general methods used for drying transformers. One that has been used the most and the longest is the circulation of current through the transformer windings with one of them short-circuited and sufficient voltage impressed upon the other to give the desired value of current. In applying this method the transformer may be outside of the tank or inside, with at least the manhole cover removed and with any opening in the base that is convenient. This method is now little used, principally for the reason that with high-voltage transformers the insulation between windings and between winding and iron, is so great as to place most of it practically out of the range of the effect of the heat generated in the coils. Also, notwithstanding that it has been used so long, it requires great care in its application to prevent damage to the transformers from excessive current.

Another objection to the use of this method where a transformer has been exposed to unusually severe conditions of moisture, is that in shell type transformers practically no heat extends to the punchings of which the core is built. A surprising amount of water is sometimes found between punchings. This water is not immediately dangerous, assuming the coils and insulation to be dry, for the reason that when it is driven out in service, it usually gravitates towards the bottom; but its presence has been responsible for mysterious accumulations of moisture in the bottom of transformers after they are put in service.

The vacuum method is the second oldest method. Under this method the transformer is put under the short-circuit run and its tank made vacuum tight. The windings are usually run at a temperature of from 80 to 90 deg. cent. and the tank is held under a vacuum ranging between 20 and 28 in. (50.8 and 70.8 cm.). To obtain good results it is necessary to have a high degree of vacuum, for the reason that the temperature is so very uneven throughout the transformer structure.

TABLE II

TABLE OF BOILING POINTS OF WATER

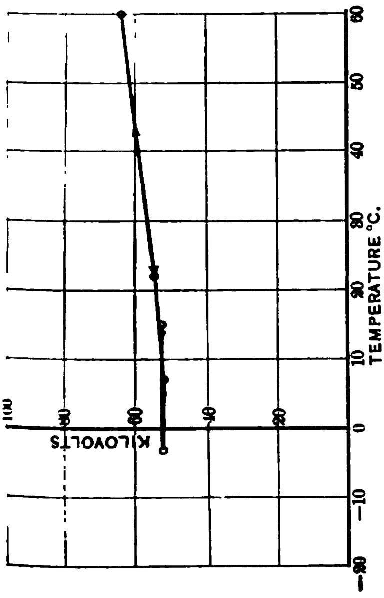
Degrees cent.	Inches vacuum	Centimeters
5	29.7	75.3
10	29.6	75.1
15	29.5	74.8
20	29.4	74.6
25	29.0	73.6
30	28.7	72.9
35	28.3	71.0
40	27.8	70.5
45	27.1	68.7
50	26.3	66.6
55	25.3	64.1
60	24.1	61.0
65	22.6	56.5
70	21.1	52.2
75	18.6	46.5
80	15.9	39.2
85	12.9	32.2
90	9.2	22.5
95	5.0	12.7
100	0.0	00.0

Under the vacuum practically only radiation gives distribution of heat, as there is no circulating medium for distributing it. The coils, where the heat is generated, are hottest; but the insulation between high-tension and low-tension windings and between the windings and iron, upon which the transformer must rely for its strength, does not reach a sufficiently high temperature to bring it within the limits of temperature and vacuum necessary to cause the moisture to vaporize. All of those parts that do come within such limits are made dry. Furthermore it is rare that a transformer is built upon such close margins that even a small amount of drying will not prevent its breaking down under normal operating conditions. Unless the transformer tank and cover are made especially tight, it is difficult to obtain the necessary vacuum. All around, the most satisfactory method of drying is the circulation of large quantities of heated air through the transformer. This method gives practically uniform temperature throughout the transformer structure and does not require a skilled electrical operator. A unit consisting of electrical heater, small blower and motor has been developed which is light and cheap.

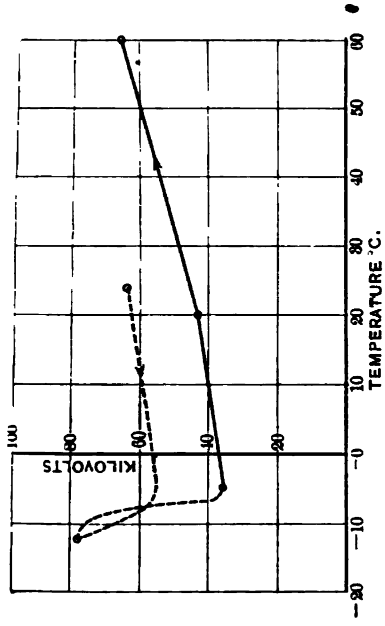
One of the problems of the outdoor installation, apparently difficult to be taken care of, is a place to put the transformers while they are being dried. Probably not more than one at a time can be placed in the repair house. For this reason it is necessary to consider drying them in position out of doors. Assuming heated air to be circulated for drying, there does not seem to be any objection to making the cover water tight and piping the outlet from the cover in such a way as to prevent the entrance of rain. Also temporary housing can be placed over the intake of the blower.

Only a few years ago not much attention was given to drying out transformers, but in later years very close attention has been given. Formerly transformers failed occasionally between high-tension and low-tension windings and between windings and iron, which was a pretty good indication of moisture; but latterly, since the use of more care in installing, there have been practically no such failures.

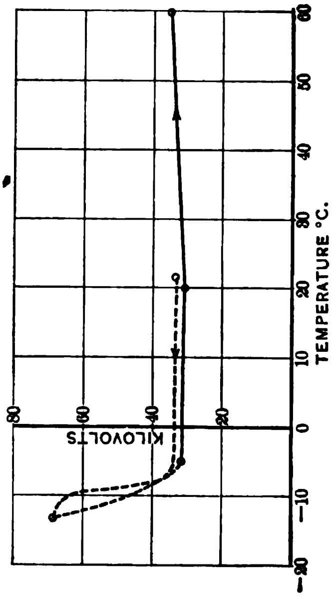
The problem of drying oil has been a difficult one to solve. Numerous methods have been used. The principal ones are: forcing hot air through oil under high temperature; heating the oil to a sufficiently high temperature to cause the moisture to vapor-



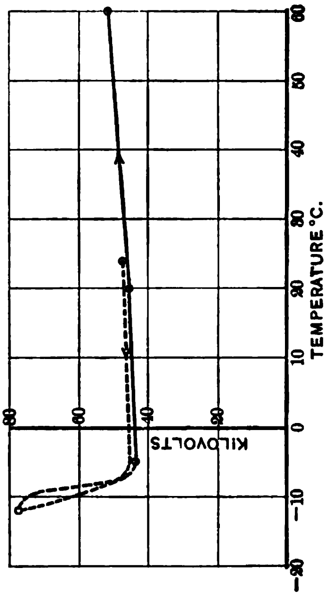
Curve 1—No. 7 low cold test oil



Curve 2—No. 8 transil oil



Curve 3—No. 10 transil oil



Curve 4—No. 6 transil oil

Dielectric Strength of Oil at Various Temperatures

Oil spark gap, ½-in. disks, 0.2 in. apart ize; heating the oil sufficiently to produce vaporization of the moisture with the oil under vacuum; forcing the oil through chloride of calcium, or lime, and sand; forcing the oil through dry blotting paper. The filtering methods are used mostly now. The blotting paper filter has proved most satisfactory. The paper constitutes a reliable and convenient filtering material with which oil may be treated to withstand a puncture voltage of 40,000 to 50,000 volts between ½-in. (12.7 mm.) disks 0.2 in. (5 mm.) apart. The necessity of heating the oil, which is always dangerous and injurious, is eliminated. All foreign matter, such as sediment and scale, as well as moisture, is removed.

OPERATING

If the planning and building of power plants have been characterized by the extravagance of too liberal consideration, it can be said of operating that there has been equal or greater extravagance in the absence of thoughtful consideration of any kind. Whether the power plants throughout the country can be said to represent good business judgment along lines of economy, may be questioned by some. On the other hand it is only within the very recent past that, even in the most progressive and extensive power systems, much attention has been given to operating features. Efforts along operating lines have been confined to those activities necessary in keeping the system going, and not much thought has been directed towards the prevention of accidents that interfere with service.

The consideration of effective economy is forcing the realization that there is much opportunity for saving, in guarding against conditions which have a tendency to bring about preventable trouble. In the past, commutators have been wiped and occasionally turned down; the dust has been blown from revolving machinery; bearings have been oiled. The time is now in sight when, in addition to these necessary and ancient operations, the right switch will be closed in the right order; oil in transformers, lightning arresters and switches, will be periodically inspected and treated when necessary; transformers will be inspected and cleaned; they will be kept cool; numerous other operating features that involve possibility of much accidental loss, will be duly considered.

There is no question that much extravagance has resulted from inattention to transformers in service. They are designed and built for a given temperature rise ranging between 30 and

50 deg. cent., but these limits have been used simply as standards for purchasing and not for operating. The cooling coils of water-cooled transformers have been allowed to become lined inside with foreign substance, or the section of the cooling coil has been restricted by the residue of chemical action between the water and the cooling coil. Water has been allowed to become heated or too small in quantity. All of these conditions tend to cause the oil in the transformer to heat excessively, which results in deposit on the surfaces of the cooling coil and on the surfaces of the parts in which the heat is generated. The efficiency of the cooling coil becomes very low, the transformer deteriorates and finally breaks down for some " unknown " reason. In the case of the oil-cooled transformers, buildings are not properly ventilated. The oil heats excessively and throws down deposit, which is an excellent insulator of heat. The temperatures run higher and higher and finally the insulating material becomes weakened.

To obtain a more comprehensive view of the importance of the situation, we will assume a transformer for high-tension transmission, so built as to easily withstand in its normal condition, the usual amount of high voltage disburbances. Let us assume that the ordinary procedure is followed in the operation of the transformer, which means that practically no attention is given it. For reasons which nearly always exist, heat begins to cause a deposit from the oil. This deposit settles on surfaces and prevents sufficient cooling. The transformer lasts perhaps five years to fifteen years, depending upon the severity of the heating and of the operating conditions. This represents the true story of the life of a great many transformers.

There does not appear to be any sufficient reason why the life of a transformer should not be indefinitely long. It is only a question of attention to prevent the conditions that result in a short life. It is evident that even the effects of long-continued mild heating must be taken care of. It is imperative that excessive heating be prevented, if the possibility of length of life is to be taken advantage of. Moreover it is obvious that the period of the summer months is the one in which the mischief is done. Air and water used for cooling transformers are much hotter in the summer time than during the rest of the year. Therefore, the problem comes down to taking care of the cooling during the summer months.

The most attractive proposition seems to be the adoption of the oil-cooled unit for the outdoor installation. It is built for the ordinary temperature rise of 40 deg. Installed, it has around it the cylinder of insulating material which has been referred to. This cylinder not only keeps off the direct heat of the sun but slightly increases the circulation of air. Under these conditions the temperature would not be excessive during nine months of the year, but the other three months are the critical period. To take care of this period, an electrically driven blower is used to produce artificial circulation between the insulating casing around the transformer, and the tank. Tests which have been made show that the capacity of the transformer can be easily increased 50 per cent for the same temperature rise. This extra capacity is ample to lower the temperature sufficiently in the summer time to prevent dangerous effects under normal loads. Running under these conditions, the oil should be noted at least twice a year and the transformer examined whenever the condition of the oil indicates the probable necessity.

For treating the oil while the transformer is in service, the filter press has been found to be highly satisfactory. All that is necessary is to attach the suction connection of the press outfit to the valve in the base of the transformer and pipe the discharge of the outfit to the connection for this purpose. Even when the best of care is taken of transformers, it is well to filter the oil at least once every two years, and in case any appreciable discoloration is noticed it should be filtered oftener. By thus keeping the oil clear of any deposit that may result from heating, the surfaces inside the transformer will be kept clean, and efficient in the dissipation of heat.

SUMMARY

The principal advantage of the outdoor station is in lower first cost of plant. Another important advantage is that the layout may be enlarged or modified at a much less cost and inconvenience than an indoor station could be enlarged or modified for. There is less fire risk. The cooling of air-blast and oil-cooled transformers is more efficient.

Some apparent disadvantages are the installing of apparatus outdoors; the possibility of the entrance of moisture into the apparatus; handling apparatus outdoors in bad weather; meddling with the apparatus by trespassers.

According to the construction being adopted for the support of outside buses, there is no chance of a person's coming in contact with the wiring unless he climbs upon the apparatus or upon the structures. All wiring is out of his reach. However, trespassers can be kept out by building a fence around the installation.

Judging from the experience, it will not be as difficult to keep moisture out of the apparatus as it has seemed to be. In fact, there does not seem to be any very serious objection that cannot be overcome. Perhaps the one objection that will prove to be the most serious, is making temporary changes that may be occasioned by unexpected accidents, in very bad weather.

This is particularly true with regard to high-tension oil switches. On account of moving parts, they are more difficult to protect against the weather, and are therefore more liable to require repairs resulting from weather conditions.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 16, 1912.

ARC VS. TUNGSTEN STREET-LIGHTING IN SMALL TOWNS

BY C. E. STEPHENS

PURPOSES

Early in the 15th century street lights were ordered in Paris, France, to prevent crimes of violence. This was at a time when the only occupants of the streets after night were belated pedestrians and a few vehicles. In the present day the use of our streets by night is growing and ever increasing. In fact the traffic in certain sections is heavier, in some cities, during the earlier part of the evening than it is at any time during the day. It is necessary to provide street illumination to mark the course, assist the police, also to avoid obstacles and to recognize persons. Police require to observe suspicious characters, and to see numbers on automobiles.

It is difficult to estimate the value of good street illumination, nevertheless it is positive. The best lighted streets attract the largest crowds. An increase of intensity of illumination increases the traffic, and property values fluctuate with the density of the crowd. It is a noteworthy fact that, in many of our cities and boroughs, one street or section thereof, or perhaps one side of a particular street, is congested with traffic, while other sections in the immediate locality are practically deserted. In some cases this can be attributed to the character of the business houses,but in a large proportion of the cases, there is no doubt that the illumination of the several sections is responsible for the condition. There is, therefore, at the present time a far closer relation existing between public safety and adequate street illumination than existed two or three hundred years since.

The appearance of our streets gives the visitor a favorable or unfavorable impression of the city's thrift, depending very largely upon whether or not the illumination is adequate. Well lighted streets have a wholesome appearance which is an incentive to cleanliness.

Very little need be said to convince the average citizen of the positive value of well lighted streets. It remains, therefore to profit by the experience with the various systems in use and to select the one which more nearly fulfills the requirements of local conditions.

In this connection we may mention some of the defects in the present practice. There is no doubt but that as a whole, street illumination in American cities is inferior to that of European cities. This is generally understood to be for the reason that European cities have a far greater number of inhabitants per square mile than do American cities, and a lower cost for labor and material in properly maintaining a lighting system, both of which combine to reduce the proportional cost per inhabitant of lighting the street. We believe the chief cause to be that the American public has not been educated to the value of an improved standard of street illumination. This standard has increased wonderfully within the last five years, but there is room for great improvement. A greater number of lamps in some cases, and in others units of greater candle power, have been installed as a result of a spirit of cooperation among the lighting companies.

The principal defects in the past have been the absence of a properly diffused light and the use of high brilliancy units so placed as to violate the physiological requirements for satisfactory street illumination. This applies particularly in sections where the cost prohibits any class of illumination other than that of a lamp used for a marker.

Until within the last few years, very little attention has been given to scientific illumination, either in commercial, industrial, residential or street lighting. The first improvements were made in the industrial and commercial field. The progressive and successful industrial and commercial concerns soon realized the necessity for better artificial illumination, in order to improve the quality, and increase the output and efficiency of their organization. This resulted in an application of scientific principles of illumination in their establishments which has been followed to a limited degree in residential lighting.

The long period of insufficient and generally unsatisfactory illumination of the streets is now being succeeded by a period in which central stations, civic organizations and merchants are making a gigantic effort to improve conditions. This effort has resulted in the installation of a large variety of lighting systems.

Great progress has been made in educating the general public to a higher standard of street illumination. To a limited degree citizens have begun to realize the inestimable value of a higher standard of illumination. We have installations worthy of considerable praise, but as yet the improvements of which we boast do not compare favorably with the standards set in other lines of civic betterment.

GENERAL CONDITIONS

The fundamental problem to consider in the illumination of any street is the intensity of the illumination required and its production at a minimum cost. The cost includes the expenditure of energy, cost of maintenance, and interest and depreciation of the lamps, plant and all auxiliary equipment.

The area to be lighted is a long and comparatively narrow strip.

The intensity of illumination is proportional to the light intensity of the unit and inversely proportional to the square of the distance from the light source. Assuming that for a given minimum illumination a certain distance between lamps is required, if this distance be doubled, each unit must have four times the light flux and each mile of street will require two times the energy. Inversely, if the distance between units be reduced one-half, to get the same minimum intensity of illumination will require only one-fourth the light flux and one-half the energy. If the problem could be solved on an energy basis alone, it would therefore be logical to use a maximum number of light units with a corresponding reduction in their flux and energy consumption. It will be noted, however, that increasing the number of units also increases the installation and maintenance cost of the system. There is a point beyond which the cost for any increase in the number of units will exceed the saving in energy consumption. A point cannot be fixed which will apply generally on account of the innumerable variables (such as the intensity requirements in different sections of the city, obstacles which prevent a proper location and distributions of lamps, energy costs, etc.) which are involved.

When considered from the standpoint of economy without regard for illumination and decorative requirements, if energy cost is low, large units at great distances apart are better, and if energy cost is high, small light units placed at frequent intervals are more economical.

It should be noted that the above applies only to the illumination of long and comparatively narrow areas where the flux of light required varies with the distance between units, that is, when the distance between the units is doubled, the area which a particular lamp must light is only doubled. This does not apply in the illumination of large rectangular areas where the light units are placed on the basis of the square, since under these conditions when the distance between units is doubled the area which each unit must light is increased to four times, the total light flux is increased four times, (to maintain the same minimum intensity of illumination) and the efficiency remains the same.

In street lighting, therefore, to keep cost within reasonable limits the intensity of illumination is necessarily very low. Heretofore we have had to be satisfied with a spot light form of illumination in our streets, but recent improvements in efficiency and the satisfactory operating characteristics of our most modern street illuminants make it possible to light our streets economically and comfortably by night. The increased standard of illumination of the street has become necessary on account of the extensive use of our streets at night. The character of this illumination is general as distinguished from local lighting, and on account of the low intensity should be quite uniform or else effective illumination midway between lamps will be further reduced by the points of high intensity immediately under the lamp.

Having mentioned some of the general requirements of street illumination, it is in order to discuss conditions, quantity and quality of the light and to note its relation to intensity.

The requirements for good street illumination may be considered under the following heads:

Uniform intensity; distribution.
Diffusion.
Intrinsic brilliancy of light source.
Shadows.

We see things by virtue of their difference in luminosity. Difference in color at low intensities is barely discernible, and regardless of the quantity of light received by objects, the difference in the amount reflected to the eye from black objects and bright objects is comparatively small. That is, a black object will reflect approximately 25 per cent of the light reflected by a bright object. The ability to perceive objects, therefore, depends upon the capacity of the eye to distinguish differences in luminosity. According to Fechner's law the eye can perceive, over a wide range of intensity, a fairly constant fractional difference in luminosity. In bright light it ranges from one-half of one per cent to one and three-fourths per cent. This difference decreases with light intensity until at one lux the eye is hardly able to perceive shadows. The ability of the eye to perceive differences in luminosity depends largely upon the condition of the eye. If the eye is adapted to the dark, shade perceptions are possible at extremely low light intensities.

In street lighting if you can see an object fairly well between lamps, *i.e.*, at the point of minimum light intensity, the ability to see is materially affected by glare, and to changing of light intensity due to moving along the street. It is of importance, therefore, to provide a uniform intensity of illumination, particularly in streets where intensity is low, and to select, equip and locate the light source to avoid glare.

By uniformity is meant a uniform illumination at all points throughout the length of the streets. At street intersections and other points where traffic is likely to be congested a higher intensity of illumination is needed. The intensity at these points can be ten times that of the minimum illumination at other points and not be objectionable, since there are no moving vehicles which will approach alternate light and dark spots so fast but that the eye cannot easily accommodate itself to the different intensities of illumination. Assuming the minimum intensity of illumination as unity, the ratio between maximum and minimum illumination for business or other sections of the street where a high intensity is maintained, should not exceed ten to one. For residence sections, parks and outlying districts the ratio should not be greater than five to one. This ratio of maximum to minimum illumination is smaller in the latter case because of the fact that where intensities of illumination are quite low the effect of the comparatively light and dark spots produces objectionable glare. Furthermore, it is in these sections of our streets that are found the fast moving cars, automobiles and carriages. Uniformity is of greater importance, therefore, in the residence or other sections or cities where low intensities of illumination prevail, and of less importance in the business sections where high intensities are used.

To produce a uniform intensity of illumination on a horizontal plane, a certain intensity of distribution curve and a certain location of light sources is required. The uniformity of illumination with a given unit varies with the distance between units and their height. The very nature of the street area determines that the light units must be in a single or double row along the street. The number and size of units and height of units are determined by the intensity requirements and cost of operation. In making a selection of units for a given condition it is necessary, therefore, to carefully consider the curve of light distribution of the available units. Increasing the height of the lamp decreases the intensity of illumination directly under the lamp quite rapidly and does not materially change the intensity at greater distances from the lamp. The height of a lamp is usually quite limited on account of the extremely high cost of installation, maintenance, tree obstruction, etc.

A long experience with the old open arc lamp has demonstrated that in any illumination scheme it is objectionable to use a source from which the light flux issues from a point. This is particularly true in street lighting where relatively large units are employed, since it is impracticable to support a lamp at such a height that it will not come within the field of vision at a time when the observer is quite near the lamp. It is not feasible to change the nature of the light source, but by an intelligent use of the available glassware for modern street lighting units it is possible to diffuse the light quite satisfactorily. The most objectionable features of an improperly diffused light are the high intrinsic brilliancy and the resultant sharp shadows cast by the illuminated objects. The extreme brilliancy of an improperly diffused light, when within the field of vision, causes a contraction of the pupil of the eye and produces the same physiological effect as if the intensity of illumination were reduced. There is considerable loss in light flux when a diffusing medium is used (due to absorption), but the final result will ordinarily be far superior because with the reduced light flux a greater proportion of the light will enter the eye.

The shadows of an object when illuminated by directed light are very sharply defined and terminate abruptly. This is particularly noticeable in street lighting where they are exceptionally long and project lengthwise of the street. This is very objectionable from the standpoint of proper illumination in that it makes it quite difficult to clearly distinguish the outline of small obstructions, magnifies the size of the object, and the result is unsatisfactory illumination. To minimize this effect demands that a source of light should be thoroughly diffused (issue from a large source) in order to prevent sharp shadows, and be as high above the point as possible in order to avoid excessively long shadows.

CLASSIFICATION OF STREETS

The wayfarer wants to distinguish the shadow of a post from a hole in the ground; and the policeman to distinguish a peaceable citizen from a burglar. In some sections it is desired to distinguish faces, read addresses, house numbers, etc. It therefore becomes necessary to classify the lighting undertaken and to light each street according to its needs, keeping in mind the class of traffic by night and the requirements of public order.

In small towns the streets which require first-class illumination are public squares, the principal business streets, the streets leading to a railway station where vehicles and pedestrians are numerous, and certain sections of streets where crime abounds.

The streets which require second-class illumination are those where nocturnal traffic is light or moderate. Such streets are the quiet residence streets, the business streets on which there is little traffic by night, and the outlying streets which are the principal thoroughfares to and from the country or neighboring towns.

The streets which require third-class illumination are those in the outlying portions of the town, perhaps not built up, but are within the city limits.

In small towns or cities very little first-class illumination is required, since the traffic is rarely very dense and the area of the streets under this classification is comparatively small. The intensity of light required is lower than in similar sections of larger cities, and from a physiological standpoint there should be sufficient reading illumination for a minimum value. This intensity is usually set at approximately 0.8 average, with a minimum of 0.4 lux. The standard of intensity of street illumination has been steadily rising in this country, and the small town has found it difficult, owing to the large amount of street mileage compared to property values, to keep up with the pace.

The intensity of light required for second-class streets should be sufficient to read an address and to see house numbers, and should be an average of 0.4 with a minimum of 0.25 lux.

The third class of illumination should be sufficient to avoid other wayfarers and objects. No attempt can be made to illuminate the street but markers should be provided at street intersections.

Light Sources Available

The subject of this paper excludes all forms of light sources except the arc lamp and the tungsten incandescent lamp.

Arc lamps may be divided into four types; 1, open carbon arcs; 2, enclosed carbon arcs; 3, metallic flame or luminous arcs; and 4, the enclosed flame-carbon arcs. The first two types have become practically obsolete as street illuminants. The metallic flame arc has largely replaced the older forms of lamps. The color of the light is white and the distribution shows a maximum candle power from fifteen to twenty-five degrees below the horizontal. The electrode life averages from two hundred to two hundred and fifty hours, and the maintenance cost is comparatively low. The efficiency of light production varies from one-half to one watt per candle, depending upon electrode life and glassware equipment. The lamp is operated at from four to seven amperes, with an arc voltage of about seventy. It operates only on direct current and is ordinarily used on series circuits from constant-current rectifiers.

The flame-carbon arc lamp has superimposed carbons, which give a life of from 100 to 125 hours. The carbons are impregnated with a light-giving salt which furnishes a white or yellow light. The light distribution shows a maximum at from 20 to 30 degrees below the horizontal, similar to the metallic flame, which adapts it admirably for lighting streets or large areas. The volume of light is considerably in excess of the metallic flame lamp, and the efficiency of light production averages from 0.2 to 0.3 watts per candle. This lamp is the most efficient light source available for street illumination. It has been recently marketed in this country for operation on all commercial circuits, both alternating and direct current. For street illumination a series design is ordinarily used.

The tungsten incandescent lamps are available in sizes ranging from 40 to 400 candle power. The efficiency of light production is approximately 1.2 watts per candle. The light distribution, when properly equipped with reflector, shows it fairly well suited for street requirements.

An ideal curve of light distribution, from a practical standpoint, for a street lighting unit, is one having a maximum candle power from twenty to thirty degrees below the horizontal, and a rapidly decreasing candlepower value above and below these angles. By a practical standpoint we mean, when considered from the power available, the limits to the height of the lamp, and the nature of the area to be lighted.

The question of whether arcs or tungsten lamps should be used in the illumination of the streets in a small town is the old question of whether large or small units are best. In our opinion each unit has its own field of usefulness, and the requirements of the small town involve both the arc and tungsten incandescent lamps. When considered from the standpoint of illumination, a larger number of small units have the advantage in that the total intensity required to meet the conditions of maximum and minimum values is lower than for large units. It is not desirable, however, to solve the problem from the standpoint of maximum and minimum illumination alone for there are other items which materially affect the result. Chief among these is the limit to expense involved in erecting and maintaining a large number of units; the areas beyond the streets which are lighted by a larger unit; and the amount of light reflected from buildings to the street surface when large units are employed. In other words, if one large unit be replaced by a number of smaller units, under the same conditions, a reduced total light flux for the same minimum illumination is secured, but it is necessary to install and maintain a larger number of units. It is possible, therefore, that no gain in illumination efficiency is made which is comparable with the loss in light flux. Small units have a large field in second and third-class lighting, and large units in first-class lighting.

About three years ago there was started the tungsten post system of street lighting for the streets requiring first-class illumination. This system was installed quite extensively throughout the country, but recent practise indicates a logical tendency to use flame arc lamps, supported at greater heights from the street surface.

For a time the tungsten post system was a novelty and attracted considerable attention, but its disadvantages are numerous. It is impractical to supply power to the tungsten post system from overhead feed wires. This necessitates the tearing up of both sides of the city streets to install underground feed wires, which therefore makes the first cost of the installation excessive.

The first cost of underground feeders for the tungsten post system, if constructed in an approved manner, would be prohibitive. The construction is therefore necessarily a temporary job of underground work, and in case the system is unsatisfactory, or for any reason is discontinued, the underground feature would be useless.

The tungsten post system involves the erection of a large number of additional posts on the street which are unsightly and which give a " fenced in " appearance to the street.

The tungsten posts are comparatively low, since the lamps are approximately only 12 ft. (3.6 m.) from the surface of the street. The light from the lamps is therefore constantly in the line of vision and produces a glare effect in the eye that from the standpoint of good illumination is extremely objectionable. The general effect on the public may be pleasing at the start, but experience shows that after a short time the novelty wears off and general dissatisfaction prevails.

The annual maintenance cost of the tungsten post system is excessively high.and it demands constant daily attention.

We see no excuse for a cluster of tungsten lamps to provide a large unit, when the arc lamps provide such an excellent substitute with superior illumination results and a lower maintenance cost.

The flame arc system is simple and inasmuch as the lamps are controlled from the light plant and are trimmed and cleaned at regular intervals, little attention is required. The lamps give a large volume of light and when placed about 25 ft. (7.6 m.) from the street surface give a uniform distribution of light and do not produce the objectionable glare which is characteristic of the tungsten post system.

In lighting the second-class streets in small towns, trees are often encountered which prevent the use of large units. It is necessary to place the lamps low, in order to clear these obstructions to the light rays; and this low mounting height in turn determines the use of a small unit such as the tungsten lamp affords.

In deciding on the unit to be used, the choice lies between the arc and the tungsten lamp. Once the choice is made, it is then a question of spacing the lamps to give the minimum illumination and of mounting them at such heights as will eliminate glare.

The principal defect noted in a large number of arc lamp systems is the tendency to support the lamps too close to the ground. This is particularly objectionable on account of the fact that the glare effect produced by the bright light in the eye causes a contraction of the pupil, which limits the amount of light entering the eye and no advantage is gained by a high intensity of illumination.

SUMMARY

From the above discussion, it will be noted that local conditions practically determine the unit to be used. No one unit can be adopted as being the best for all installations. Assuming that all small towns have a certain amount of first, second and third class lighting, it will be necessary to use both arc and tungsten units. If the number of arcs is large enough to admit of installing one complete circuit, use can be made of either the metallic flame or flame-carbon lamps. If, however, only a small number of arcs are required, it may be advisable to use the alternating current flame-carbon arcs and operate them in series with the tungsten lamps in the residence sections.

For the second and third-class lighting, the tungsten lamp is better adapted. It is possible to operate them in series, using small units between intersecting streets and larger tungsten or perhaps arc lamps at street intersections. In any case it is advisable to raise the lamps at street intersections, in order to indicate to the driver of a fast moving vehicle that he is approaching a cross street. Long lines of lamps on the same level, particularly if they are low, tend to confuse one in rapid motion and it is difficult to see a cross street and to observe vehicles emerging from same.

Perhaps the most fertile field for immediate development is in a rearrangement of the present lighting system. It is possible to make enormous improvements on almost any system of street lighting by relocating the lamps; raising them higher from the street; removing useless, and replacing crooked, or decayed poles; and giving the lamps and fixtures sufficient attention to insure a pleasing appearance. A recent example of what can be accomplished along this line is an installation of an ornamental street lighting system of arc lamps. The novel feature of the installation is the use of the iron trolley poles for supporting the lamps. The poles were reset, where necessary, to make them perpendicular to the street surface, and a suitable iron extension post securely fastened to the top of the trolley poles. The length of this extension post was adjusted to give the lamps a uniform height of 26 ft. (7.9 m.) from the street. Substantial mast arms were designed to support the lamps from the extreme top of the poles, and the service wire is carried overhead on high-voltage insulators.

Mention may also be made of the possible improvements in caring for lamp glassware. Street lamps are subject to most severe weather conditions; dust and smoke will in a very short time have a deteriorating effect on the appearance of a lamp. A large proportion of industrial and manufacturing plants, stores, etc., have realized the advantages of keeping lamp globes and reflectors in good condition, and have had the maintenance department adopt a regular schedule for frequently washing and cleaning the fixtures. The results obtained have been highly satisfactory.

A street lighting unit is the one piece of electrical apparatus which is constantly in the public eye. Its appearance largely influences the attitude of the general public toward the lighting company. Why, then, should it not be kept in first-class condition?

It is a matter of note that while the central station managers have taken advantage of the many refinements in power station designs, have so regulated the power demands that the revenue is a maximum for the minimum station expense and have installed the very best generating equipment available, they have only quite recently turned their attention to the efficiency of the distributing lines and lamp fixtures which are just as essential to the successful operation of a lighting system.

No doubt the central stations have been greatly handicapped in their efforts to improve street lighting conditions by the vast amount of unreliable data which is frequently published. We often read articles in local papers in which the rates for street lighting service in various cities and towns are compared. These articles appear quite frequently during the time when a new contract between the light company and city is pending, and are sometimes very inaccurate and misleading. The data are generally inaccurate, not in the information given, but in the lack of complete information.

Local conditions again are responsible for the excessive variation in street lighting rates. In some cases a very low rate is given by a municipal plant, because of the fact that the accounting methods used do not take into consideration all of the items properly chargeable to the service. Maintenance and depreciation on distributing and plant equipment, interest on investment, pole taxes, etc., are often neglected. Other items, such as coal, water, etc., in combination water and light plants, are charged to other departments of the city government. The result is a very low rate for street lighting service which does not represent the true cost.

In other instances, central stations make a very low rate for street lighting service, in exchange for a long term franchise for commerical light and power privileges. Another city secures a low rate for street lighting from a central station enjoying water power privileges, which conditions are not justly comparable with rates from another central station, perhaps many miles from a coal and water supply.

DISCUSSION ON "ARC VS. TUNGSTEN STREET LIGHTING IN SMALL TOWNS" (STEPHENS), PORTLAND, ORE., APRIL 16, 1912.

Gano Dunn: It is a deep satisfaction to see that the author of this paper has found in the Institute the forum where it may be presented and discussed instead of finding that forum in the Illuminating Engineering Society. The author followed good precedent. Illumination has been a close cousin if not a nearer relative to electrical engineering, and I think it always will be.

The general features of the paper indicate that the various qualities of illumination as presented differ from each other principally in the arrangement of units, in the methods of producing illumination, rather than in the electric means devoted to the actual creation of the light. When we get illuminants down to two-tenths or three-tenths of a watt per candle power we are arriving at an efficiency which used to be regarded as heralding the approach of the days of cold light. We have passed through, in recent years, marvelous improvement in incandescent lighting, with the practical doubling of the efficiency of illumination by the introduction of the tungsten lamp, and its influence is not yet fully realized, for the public is hardly yet aware of what has happened.

It is very natural that the two forms of illuminant should compete with each other. My prejudice—we all have prejudices—in fact, as a celebrated university president has said, most men feel instead of think—my prejudice is in favor of small unit distributing sources of illumination as against large units concentrated. But to show how neither one of these is the correct illumination for every case, we have only to read the paper very ably prepared by Mr. Stephens.

The psychology or physiology of electric lighting is the direction in which perhaps the greatest improvements have been made recently. The arc lamp has always been a lamp of high efficiency and power, but the flaming arcs have made no more rapid advance in arc lighting than has the tungsten lamp in incandescent lighting, so it is about right to say that the race is approximately even between the two types of illuminants. On the physiological side we find the law referred to and a general recognition of the fact that the very brightness of a light often contributes to make us think that the illumination is bad instead of good. An intensely bright light in a room depreciates the value of the illumination in practically every part of the room except the particular part it occupies. It is a realization of this which has led to such expedients as frosting the globe, the use of groups of small units, as in cove lighting, and indirect lighting in general, also tubular lighting, and is exemplified by the Moore system.

I once made a technical examination of the Moore system and was astonished to find that the illumination did not vary inversely as the square of the distance. At first sight this looks like an inversion of the laws of nature. The reason ordinary illumination varies inversely as the square of the distance is that it proceeds from a point. The Moore light and other tubular systems, including incandescent lamps that are strung out in the form of tubes, may be regarded as sources in which the illumination proceeds from a line instead of a point. Its intensity then is inversely as the distance instead of inversely as the square of the distance.

I would call the attention of the members to a feature in the paper which may interest them. You have probably noticed that the engineering data, rates, volumes, etc., are followed in parentheses by their metric equivalents. Some may think this is not necessary, but I should like to tell what was done at the International Electrotechnical Congress in Turin last September. So greatly appreciated was this practise instituted by the American Institute of Electrical Engineers in giving metric equivalents in parentheses, that the Congress as a whole unanimously passed a resolution expressing its appreciation of the custom of the American Institute of Electrical Engineers and recommending that all electrical societies using English measures follow the same course. It is little realized how much our papers are read abroad, and it is also little realized how vastly important that little parenthetical item in the paper is. For the Englishman that is not accustomed to American things, it is difficult to read an American paper. This seems a radical statement, but I have many times had evidence of it. For instance, on the question of weight. The English ton is not our ton, our hundredweight is one hundred pounds while the English hundredweight is one hundred and twelve; the English gallon is not our gallon and the English bushel is not our bushel, and so it goes on down the line. When an Englishman not familiar with these facts reads a paper of the American Institute of Electrical Engineers, the metric values enable him to know exactly what the author means. I went so far once as to be rude enough to break into a conversation of British engineers in a train from Manchester to London. I heard a British engineer complain of American engineers for false statements as to the delivery of American pumps which, he asserted, were constantly overrated. I called his attention to the fact that he was probably measuring the pump in English gallons and explained that the American gallon was only 83 per cent of the English, owing to the adherence of the Americans to the old English standards.

S. C. Lindsay: I wish to take exception to one statement made in Mr. Stephen's paper regarding the tungsten post system: "The light from the lamps is therefore constantly in the line of vision and produces a glare effect in the eye that from the standpoint of good illumination is extremely objectionable. The general effect on the public may be pleasing at the start, but experience shows that after a short time the novelty wears off and general dissatisfaction prevails." That may be true in some cases where cluster lamps are not properly arranged and distributed on the street. I would like to have the author of this paper visit Seattle and look at the lights on the streets of that city. I think he would then change his mind. I think Seattle has the finest example of street illumination from posts and cluster lights that there is in the country. I have not seen the cluster lights in all other cities, but have seen three or four other examples, and do not see how it is possible to improve on the Seattle cluster lights. I will go further and say the cluster lamps in Portland are not one-third as good.

F. H. Murphy: I wish to ask a question as to the spacing and the height of the cluster lamps of Seattle. I am not familiar with them, only having been on the coast a short time.

S. C. Lindsay: I have no data on that point; the city owns the plant and the situation and arrangement of the lamps are entirely in the hands of the authorities, and I do not happen to have the data. Mr. Howes advises me that they are about one hundred feet apart and I should think from general observation that that is correct.

A. A. Miller: I can give you a reference which you might like to look up. About a year ago last January there was a paper presented before the Seattle Section on the subject of " Seattle Street Lighting " by two university students who made that the subject of their thesis. You will find it in the files of the *Journal of Electricity, Power and Gas.* The characteristics of the lighting system are there given with the spacing of posts and number of lights per post. In the downtown section they use a five-ball cluster arranged in an inverted V, with the point at the top, claiming that the distribution of the light in the street is better that way than if arranged in the form of a rectangle or otherwise. In the second-class district, according to the classification in Mr. Stephens' paper, they use a three-ball cluster and in the parks of the city a single ball is used. I do not remember the candle power of the units in the different clusters; that is all given in the paper referred to. The height is, I should say, approximately 15 ft.

Gano Dunn: One statement in the paper that attracted my attention, was the one in regard to the glare from tungsten clusters, which has been already questioned by Mr. Lindsay. I doubt whether it is a discriminating statement. If you have a cluster of tungsten lamps, say, one hundred feet away and twelve feet high that gives a brilliancy that is going to be no more in the line of vision than the brilliancy of an arc lamp two hundred feet away and twenty-four feet high and four times the intensity. I do not think the case made out against the tungsten lamp is a good one in that respect.

F. H. Murphy: I would like to call attention to another point in the matter of cost. The statement was made in the paper, I believe, that the cost in small units is greater on account of the greater number of posts. It is true, of course, that in order to give the proper lighting by the flaming arc lamp, or luminous arc, it is necessary to hang it considerably higher, which of course requires more expensive posts and will partially counterbalance the cost of the greater number of small posts. I think that ought to be taken into consideration in making a comparison of the costs.

H. M. Friendly: I would like to make a few remarks in reference to street lighting by means of tungsten lamps within the business section of both small and large cities—remarks that are not at all technical, but more from the point of view of the ordinary citizen, the man who pays the bills.

It has been the custom to mount these lamps in clusters on posts. Where the streets and sidewalks are narrow it gives the effect of narrowing both the street and sidewalks, and the posts do seriously obstruct the latter. The pedestrians must keep within the inner line of the posts, and these are usually set about eighteen inches from the outer edge of the walk, thus, in effect, reducing the sidewalk width by that much.

It appears to me that an artistic and ornamental bracket of some kind could be easily designed, having a graceful downward sweep that would be readily adaptable to any buildings such as would be found along a business street, and then mount the tungsten clusters pendant from the outer end, which could be on a line with the outer edge of the walk. The lighting distribution would be quite as good as from posts, and the fixtures would be far less noticeable during the daytime.

The arc lamps with their relatively few posts at least do not obstruct the sidewalks so seriously. In the Portland business district, the tungsten lamp posts are a nuisance.

G. R. Cooley: It sometimes seems that the cost of installation of cluster lighting is only a minor consideration. We found in Seattle that the property owners were very willing to stand all this cost themselves to be able to have this particular style of lighting, and it became necessary for the City Council to refuse to let the property owners put in cluster lighting because the council could not see its way clear to furnish the current they wanted. The people were so much taken with this system of cluster lighting that they were anxious to have it, and it was even put on streets where there were no buildings for blocks and blocks at the sole expense of the property owners. The council had to cut out some of the lights because there was no necessity for them there. We use the frosted ball with a tungsten light and have had no difficulty, and as Mr. Lindsay said, we have a perfectly installed system.

W. A. Hillebrand: The title of Mr. Stephen's paper is "Arc vs. Tungsten Street Lighting in Small Towns." I wish to refer particularly to small towns and especially to conditions on the Pacific Coast. The smaller towns in the Northwest are of recent growth, very recent compared with the smaller towns in other parts of the country. The town has to pave its streets, provide sewers, sidewalks, water systems, curbs, parkings, etc., and I think you will find that in some places the taxes run as high as four per cent. A system of ornamental street lighting is simply adding another expense. It seems to me that this matter ought to be carefully considered.

The influence of a city like Portland can hardly be over-estimated in its effect upon all the small towns within a radius of one hundred miles. For instance, I fully expect to see a gradual and steady increase in the amount of tungsten post lighting in the smaller towns throughout the state, simply because Portland uses that system extensively. A conspicuous example is a little town about forty miles up the valley, through which you passed on the road. I don't know what the per capita cost of such a lighting system comes to, but it seems to me that it is highly questionable whether the average town can afford lighting of that nature.

R. Howes: I wish to bring out one point that I do not think has been touched upon regarding the lighting of Seattle. The clusters on the main avenues consist of five lamps, one above at the top, and two a little lower one on each side, and two more still lower, one on each side, and the clusters are spaced opposite each other, that is, both sides of the street are lighted. I do not remember the exact distances between clusters, but I think it is about one hundred feet—not more than that. This arrangement of five lights prevents the casting of any shadows on the street by nearby poles and other structures, whereas the concentrated light of arc lamps casts dark shadows on the street. I think that is one reason why the Seattle lighting is so attractive to the people that come there.

If strong lights are placed only at the intersections of streets, they light up the crossings for approaching vehicles.

If the same amount of light were distributed uniformly along the street, I think that advantage would be somewhat less.

Gano Dunn: You mean that you like the spot light at the street corners better than the distributive illumination?

R. Howes: No, but I mean it brings out the crossings to the people riding along the street. While they may be blinded at a distance, as they approach the light and pass under it they can see on either side. If arc lights are distributed uniformly along the street without regard to the crossings, as is done in some places, the benefit of this effect is lost, just as with distributed tungsten lights.

George H. Sampson: The last speaker spoke about putting the arc lights closer. Where the street car systems have poles in the center of the street, the arc lights are put on those poles, and it gives a very fine average distribution. I should say it means about 100-ft. spacing.

J. B. Fisken: I hoped when I saw the title of this paper that there would be quite a discussion on the lighting of small towns.

We have heard something about the lighting of small towns, particularly Seattle, and Portland and San Francisco, but there are other small towns that we have not heard much about. I agree with the author that enclosed carbon arcs are practically obsolete. I can endorse that statement because our own town is lighted that way. It happens that we have a contract calling for 500-watt arcs which cannot be changed until that contract runs out. Another statement of the author's I thoroughly agree with, that it is impossible for the average man to know what it costs a municipal plant to do lighting.

The company I am connected with has the distribution system in two small towns at present and expects in future to control some more. We bought a plant at Colfax, a town with population of four or five thousand, that is, we bought the existing plant. It was lighted with arc lights spaced at irregular intervals, and of irregular illumination. The people were very much dissatisfied and when we bought the plant and applied for a franchise we took the opportunity of getting a new street lighting contract. We took it on the basis of a series of tungsten lighting system, the lamps being suspended across the street intersections. I don't remember the details of the contract, but we had a certain number of 250-watt tungsten lamps spaced about 300 ft. apart in the business part of the town, and on the outskirts 100-watt tungstens at reasonably close intervals, not very close, but fairly well spaced. The approval which the new system received was very gratifying. We had a great many citizens come to us and say how pleased they were with the change. We didn't have the brilliant spots, but the street looked well lighted. In another small town of about eight hundred inhabitants, where we installed these lamps, we followed the same plan and it has been very satisfactory. I would like to hear from any who can give experiences in other small towns.

A. A. Miller: There is one point that I do not think has been brought out, with reference to the "fenced-in" appearance of the street when it is lighted by tungsten posts. All depends on the point of view. The smaller towns to which this paper applies invest a certain amount of money in street lighting systems. I think the average citizen rather than feeling a sense of being fenced in, feels a sense of pride in being able to see in what he has invested his money. If one goes into a small town at night and sees a pleasing illumination of the main street by post tungstens it has a certain effect in raising one's estimation of the progressiveness of that town. In the daytime that "fence" is in evidence, but I do not believe that it is displeasing. There I do not agree with the author. In a large city, where ordinances have been directed against poles carrying overhead wires, which ordinances resulted in underground distribution, that might apply. But even in our largest cities, where the wires have been put underground, I do not think the effect of a long row of well-proportioned tungsten posts is unpleasant to the eye, especially at night.

Alexander Martin: I have had some experience in the last few months in connection with street lighting in several small towns in eastern Washington. Three of them, particularly, I would like to speak about—Pomeroy, Dayton and Kenewick, Washington. I found that in all these towns, under the old system before reconstruction they had 16- or 32-c.p. multiple lamps connected to the secondary system. In reconstructing the systems in these places, we replaced them with 6.6-ampere series tungsten lamps. At Kenewick we are using 80-c.p. at Dayton 60-c.p. and at Pomeroy 80- and 40-c.p. series tungsten and four series arc lights on the main street. In Dayton the city has placed 31 three-light posts on the main street, covering a distance, as I remember it, of about a thousand feet. This gives very satisfactory illumination for the main street. In the placing of the series tungsten lamps we are using a five-foot bracket and putting the poles on which the brackets are hung at the curb corners, the brackets coming out over the street at an angle of 45 degrees; the brackets are placed at a distance of about nineteen feet above the ground. We are using the Cutter type of reflector made for this work, and find the results very satisfactory.

The important consideration in all these towns is the expense. There are very few of them that could afford much cluster lighting, and unless the business interests and people get together and carry most of the burden, the city cannot consider it. When it comes to placing the smaller lamps on the street for general illumination, they are able to do it, and find it gives satisfaction, and good lighting effects. In hanging these lamps, if you have an alley distributing system, it becomes necessary to have extra poles to take care of the brackets. With a series tungsten system, such as I have been describing, we use 30-ft. poles on the street corners, where there are no other lines at the present time, or are likely to be in the future. This is governed by local conditions. In other places we have to install longer poles in order that additional lines may be run at some future time. Where there are lines already on the street, we place the poles so that we can use them for the street lighting brackets as well. For the small towns it seems to me the best thing is the series tungsten lamp. I believe we get better results for the money spent, and it keeps within the limit of expense to which the average small town can go. While it is possible to place cluster lighting on a few blocks of the main street, they cannot indulge in much of it because of the expense.

O. B. Coldwell: The company with which I am connected has service lines in a number of small communities, and it might be of interest to state that in a number of them what we would now call the old-style series alternating lamp is in use. The merchants of the most progressive of these communities have, during the last year or two, been following the lead set by Portland, as stated by one of the previous speakers, by clubbing together and raising funds for putting in post lighting. I do not believe that in general, however, there is as strong a tendency to use post lighting for street lighting purposes as there is to install series tungsten lamps. I believe that for most of the instances I have in mind the series tungsten lamp works out to a very good advantage and perhaps is the best general system for the purposes of the small community. Conditions must always govern and the needs of the community have much to do with it.

In his paper, the author makes mention of one point which I think should not be overlooked in this discussion, and that is the possible improvement which might be brought about by taking care of the glassware on these tungsten fixtures. Some tests which have been made here in Portland within the last year or two have shown very marked improvement from the cleaning and taking care of the glassware. I think increases in illumination as high as 40 per cent have been obtained by simply cleaning off and dusting the glassware without even washing it. I think that Mr. Murphy could give us some figures on that point.

F. H. Murphy (by letter): In response to the suggestion of Mr. Coldwell that some of the members might be interested in the results of our investigation, I will state that the special test referred to was made in a drafting room lighted with tungsten lamps. The installation was not an exception in any way, but had the usual amount of care given to it in keeping it clean. Following complaints in regard to the lighting, we made careful tests on the plane of the drafting boards and found the average illumination to be 2.32 foot-candles. After dusting the installation we made a second set of tests at the same points and obtained an average illumination of 3.21 foot-candles, showing an increase of 38 per cent. Had the installation been washed instead of dusted it would undoubtedly have increased the illumination from 2 to 5 per cent more. We then replaced the installation with new lamps of the same wattage as the old ones (which had burned for considerably over 2000 hours) and a third set of tests gave us an average illumination of 5.52 foot-candles, showing an increase of 72 per cent over the dusted installation and 138 per cent over the installation as first tested.

Lloyd D. Gilbert: I am at present designing a cement plant at Oswego. I never had much experience in city lighting, but this is the fifth cement plant I have designed, and I have to take care of a good deal of outside lighting. On the El Paso plant we decided to cut out arc lamps and use tungsten for outside lighting, and we installed, I think, sixteen clusters of four in a cluster, 250-watt tungsten lamps. After trying them about eight months we had to discard them on account of the enormous maintenance. It was simply impossible to keep lamps in the sockets. It even took more time to put in new lamps than to trim arc lamps. So after running eight months and keeping close tab on the cost of maintenance, we decided to discard the tungstens and put in arc lamps. I do not have the cost data at hand, but I remember very well that I figured at the time that I could buy the sixteen arc lamps and more than save their cost in a year, allowing a certain sum of money on each of the arc lamps for maintenance and for the trimming. The country about El Paso is very windy, and we tried every known method of supporting the lamps on the brackets and suspended them various ways, but nevertheless they would get jarred enough to break the filaments, and at last we had to discard them.

Gano Dunn: What capacity were they?

Lloyd D. Gilbert: Most of them were 150-watt, four in a cluster, in series on a 440-volt line. We had a few 200-watt lamps. What we intended to do was to have the clusters of four take the place of arc lamps; we spotted the poles here and there around the plant where convenient. We also tried a few single lamps inside, but the jar of the machinery caused their failure and we had to discard them.

Gano Dunn: A negative experience like this is interesting. I think the members here would like to ask Mr. Gilbert when it was he did this. I once had some experience in my own house, where I found it was costing me a great deal to use tungsten lamps. Then I was asked to try some new lamps brought out by two different companies, and I did try them. That was a year ago. I have not had a single one break since. Because there is so much difference in the manufacture of the older lamp and the new lamp, it would be important if Mr. Gilbert would state whether or not the lamps he speaks of were made within the last six months, or when.

Lloyd D. Gilbert: They were made over a year ago. About January, 1911, was when we decided they were a failure after an eight month's trial. I had been determined to make them a success in order to get rid of the arc lamp, which gave us more or less trouble around the plant, on account of the dust and smoke, but after giving the tungstens a fair trial, we decided that they were a failure. Our cost would be, some months, $80 to $85 for lamps alone, which absolutely prohibited the use of them.

O. B. Coldwell: I think that perhaps Mr. Gilbert's experience at El Paso was a little out of the ordinary in that the installation of four lamps in series on a 440-volt circuit, especially lamps of the 150-watt type, should be different from the ordinary installation as practised in city street lighting, or even in store lighting or elsewhere in the city, his plant being an industrial plant with a type of circuit adapted to the motors operating the cement mill. I believe the manufacturing companies now supply special lamps for series lighting and for multiple lighting, making a distinction between the two. Whether they have gone so far as that to make that distinction in lamps of the candle power or wattage Mr. Gilbert used, I do not know. I know that in the case of small lamps for sign lighting they make the distinction, and I have an idea that had Mr. Gilbert's installation been made within the past few months, his success would have been much better.

F. H. Murphy: I have observed many tungsten lamps that should have broken long before they did for the benefit of the consumer. Tungsten lamps have a rated life of 1000 hr., but I find many installations that have actually burned 3000 hr., which would hardly make them seem excessive in cost, and I have found that to be true, not only of the newer type of lamp, but also of installations of the former type pasted filaments.

A. A. Miller: I would like to ask Mr. Gilbert whether or not these lamps were pasted filaments or the wire-drawn filaments.

Lloyd D. Gilbert: I cannot tell you now; I know that I got the best tungsten lamps that could be obtained at that time, and I believe they were wire-drawn; I am not certain.

J. B. Fisken: There are two things that occurred to me in connection with this matter. I heard recently of a case where rapid destruction of tungsten lamps had been traced to a feather duster, and there was no question about it. The charwoman of a school was in the habit of going through the school rooms and dusting off the lights, and the lamp breakage was very great. That was one case. In our own practise, we get some very peculiar results in summer, when it is very dry. We were installing a distribution system in a small country town and, although the nearest live wires were twenty miles away, the wires would get so charged that the men could hardly work on them. That is the second case. It seems to me that there might be a connection between those two. If the dust were highly electrified, then, in turning on the current, there might be a strong attraction of the filament to the dust-covered bulb which would result in the complete destruction of the filaments. I do not know whether Mr. Gilbert's filaments were simply broken or completely destroyed.

Lloyd D. Gilbert: Most of them were broken. Sometimes the globe would be turned black, when part of the filament had been jarred off. In most cases the filaments would break, simply cease to burn. We found the main cause to be the jar of the wind. You know it is a pretty windy country down there in Texas. They say down there that it blows so hard it blows the chickens up against the barn and starves them to death. For a system of lighting plants in a windy country, I do not think you can install tungstens and make them work.

Gano Dunn: I saw some wire that was about the size of human hair, and was cautioned against trying to break it because it would cut like a knife. It had a tensile strength of over 6000 lb. to the square inch and that wire was a tungsten; it was slightly alloyed. It is hard to realize that a substance so marvelously strong and slightly alloyed and even when not slightly alloyed so enormously hard as tungsten is, could be so weak under the circumstances in which it is used in a lamp. The tungsten filament has just gone through a stage in its manufacture from a process by which the earlier lamps were made and under which they were almost useless for practical purposes to a process which has made them wire-drawn filaments, which in the opinion of practical men has increased their working strength ten times. It also has decreased their cost, and I should greatly deplore seeing tungsten lamps discarded or their use discontinued on account of the weakness of the filaments. I regard it as a temporary stage through which they have already gone and I believe that if Mr. Gilbert should make his installations now, he would not have that trouble.

R. Howes: The series lamp is usually a low-voltage lamp, whereas in using a multiple lamp there is a smaller filament of much greater resistance, so that I do not think 110-volt lamps used in a series should be compared with the tungsten lamp ordinarily used in series lighting, where four or six amperes are used in the circuit. I was recently asked to advise a small town up on the border in Washington, and upon learning the amount of money they had provided I found there was nothing that could possibly be gotten with the money they had and provide the number of lights desired, except series tungsten lamps, and they had to use 40-watt lamps, at that. Regarding the case given by Mr. Gilbert around a cement plant there is a great deal of noise, which is a type of vibration, and while it might not affect, very much, people that are in the habit of living there, at the same time a new arrival notices the great amount of noise, and probably the sensitive filaments also are affected by it to a very large extent.

A. G. Jones: I would like to ask Mr. Dunn if the wire that he referred to as being so strong that it would cut the hand, had had a current passed through it. My idea is that after the tungsten has been burned several hours, it materially weakens, and after current has been passed through it several hours it is very delicate.

Gano Dunn: The wire that I spoke of had not been used. It was wire to be used for mechanical and not electrical purposes.

A. G. Jones: I had a piece of tungsten filament that was intended to be used in a 110-volt lamp and attached it to a chair of average weight, and it lifted it up without any trouble, but if you should attempt to take a filament out of a lamp that has been sealed and is ready for use, you would probably break it which would illustrate the difference in tensile strength after it has been used.

Lloyd D. Gilbert: Another word regarding the installation I spoke of. We had a number of single lamps working on a 110-volt circuit. We had ten or twelve departments and we had one over each one of the doors at the main entrance. These lamps were supported on a gooseneck made of 2½-in. pipe. We also had probably a dozen and a half of them working singly on the 110-volt circuit inside. It was either the noise or the vibration from the winds that caused their destruction. All behaved alike. Almost every evening when we would turn on the lights there would be four or five out. And we had good regulation on that circuit, with no variation to speak of, as we had our own power house in which we had installed two 750-kv-a. steam turbines, with automatic voltage regulator.

L. B. Cramer: We are using tungsten lamps for train lighting, principally as an experiment at present; our trains are run over city streets to the terminal and cross about twenty street-car crossings in running over the last one and one-half miles of track. There is a considerable jar at some of these crossings, but the wire-drawn filaments in the tungsten lamps that we are using have sufficient strength to withstand shocks of this sort without breaking. We are using 120-volt lamps, five connected in series.

For this reason I am inclined to believe that there is something else back of the trouble that was experienced at the cement plant, other than a Texas wind.

Gano Dunn: I might add that just before I came away from New York the superintendent of motive power of the subway road in New York, Mr. Stott, pastpresident of the Institute, told me that after running for some time, the tungsten lamp proved a great success, and practically no difficulty was found in maintaining the lamps. They gave enormous advantages from the point of view of good illumination. I think the figures were something like this: with a 10 per cent drop in the voltage due to the starting of the trains, tungsten lamps dropped perhaps 20 per cent in brilliancy; with the same voltage drop the carbon lamp dropped, I think, 60 or 70 per cent; the difference could not be compared. The introduction of the tungsten lamps on the trains has given great satisfaction to the public, and they remain steady where the carbons used to drop out and break.

H. V. Carpenter (by letter): It seems to me that we need to recall the discussions which followed the commercial introduction of the telephone and, later, the wireless telegraph. Each of these was expected by many to displace the telegraph, but soon found a field of its own. The tungsten lamp has already proved best for the inexpensive lighting demanded in scattered residence districts and in small towns where a lower standard is acceptable, and also in the opposite field of high-class business district lighting where a decorative effect is desired both day and night. It is quite possible that the arc will hold its place in the large field lying between these two requirements, and the easy combination of arcs and series tungstens, on the same circuits, if desired, leaves little reason for choosing one to the exclusion of the other.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 17, 1912.

AUTOMATIC PRIVATE BRANCH EXCHANGE DEVELOPMENT IN SAN FRANCISCO

BY GERALD DEAKIN

A few years ago, the majority, in fact a very large majority, of those interested in the technical aspect of the telephone, considered what is now well known as the automatic telephone, impracticable for central office service, even in single office districts. This erroneous idea has long since been dispelled by the installation and subsequent satisfactory operation of numerous extensive automatic systems, many of which each include a number of large central offices. Following the satisfactory development of the central office, it was soon realized that a great saving could be made in the exterior cable plant, if small unattended or partially attended sub-offices, as they are now called, could be built, to give efficient and economical service. It will suffice here to say that the experiment was tried with the result that the sub-office is now considered a necessary adjunct to the automatic central office. The purpose of this paper, is to show that the unattended sub-office is by no means the limit of subdivision and that such subdivision has now been successfully extended to include two somewhat distinct types of private branch exchanges, one adapted to meet the requirements of apartment houses and family hotels and the other the more exacting requirements of all classes of commercial organizations and business houses. The most noticeable difference between the two is that the former is arranged, apart from some minor features, to give " in " and " out " exchange service only, while the latter is arranged to give "local inter-communication " as well. The automatic system has not as yet been applied to the larger commercial hotels where the total annual cost of the equipment involved is great in comparison with the possible revenue. At the present time, the first cost of automatic apparatus prohibits its general use in such places.

In the following pages, an attempt has been made to describe briefly, the apartment house and the commercial automatic private branch exchange systems, as developed by the Bay Cities Home Telephone Company, for general use in San Francisco, and the materials and apparatus involved; also their advantages and disadvantages, and their first and annual costs, compared with the well-known manually operated private exchange.

Apartment House Automatic Private Branch Exchange

The first exchange of this character installed in San Francisco was placed in service December 12, 1910. Since that time, 24 additional installations have been made. These exchanges now serve a total of 727 stations, an average of approximately 29 stations per exchange. The maximum installation is 70 stations and the minimum 11 stations. Each installation includes a small portable automatic switchboard and storage battery. The former contains the call forwarding and receiving apparatus and a meter for each apartment. The switchboards are installed adjacent to the terminus of the house wiring. The majority of installations have been made in unfinished basements with concrete floors, and in these locations the switchboards have given very satisfactory service. Other switchboards have been placed in small closets and in other locations having no particular value for other purposes. The apartment telephones differ in no way from the usual main line automatic sets. The public telephones, installed in some of the larger apartment houses, consist of similar sets equipped with coin machines, Fig. 1. An instrument called the "house telephone," Fig. 2, installed in or adjacent to the office, landlord's or janitor's quarters, as the case may be affords a means of intercommunication between each apartment and the head of the house. Vestibule and tradesmen's entrance telephones are included in many of the installations. Each installation made in a family hotel also includes a small receiving cabinet, Fig. 3, and a service meter cabinet, both of which are placed in the office of the hotel. The former provides a means whereby the public may call guests through the office in case the room number is not known. The latter places the meters under the supervision of the clerk and permits the rapid settling of accounts in case of transient guests.

The distinctive features of the apartment house automatic private branch exchange may be briefly outlined as follows:

1. Affords a comprehensive telephone system in which a branch exchange operator or attendant is not required.
2. Affords each apartment metered and direct " out " exchange service.
3. Affords each apartment direct " in " exchange service.
4. Affords each apartment 24-hour service.
5. Affords each apartment the equivalent of main line service.
6. Affords each apartment secret service.
7. Affords each apartment a means of intercommunication with the head of the house.
8. Affords each station direct service from vestibule and tradesmen's entrance.
9. Affords automatic pay station service for the public.
10. The switchboard may be placed in any convenient and reasonably dry location.

DESCRIPTION OF OPERATION

Outgoing Exchange Calls. A subscriber, when making an exchange call from an apartment, removes receiver from hookswitch and listens for the "busy tone," which if heard, indicates that all trunks are in use. Failing to get the busy tone, the subscriber proceeds to call the number of station wanted by turning the dial in a manner[1] now well known in automatic telephone practise. The call bell at the distant station rings intermittently until the party called answers or until the party calling hangs up in case the party called does not answer. When the distant station answers, the meter associated with the calling line operates, and registers one call; under no other condition will the meter operate. Should the station called be busy, the usual tone indicating this will be heard. When the calling subscriber hangs up, the connection is released. Calls to information, complaint or other departments of the telephone company, are not registered.

Call to House Telephone. To make a call from an apartment to the house telephone, the subscriber calls a predetermined number, such as C–05, the circuit conditions thus and only thus established automatically transfer the out-trunk from connection with the central office to connection with the corresponding answering button on the house telephone, which telephone is equipped with a key of the well known intercommunicating type, with a button for each working out-trunk. Adjacent to each

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[1] See W. L. Campbell, *A Modern Automatic Telephone Apparatus*, TRANSACTIONS A. I. E. E., 1910, XXIX, I, p. 55.

button, is a small signal lamp. Should the call happen to be made on out-trunk number 2, the lamp opposite button number 2 will light, and at the same time a buzzer will sound. The proprietor, manager or janitor, as the case may be, in answering depresses the button opposite the lamp burning, thereby extinguishing the lamp and causing the audible signal to cease. The connection is now established. The circuit of the house set is such that it can be connected to an out-trunk only when the associated lamp burns. In this way, secrecy is secured. It should be noted that no central office apparatus is involved or tied up in the completed connection. The subscriber's meter does not register these calls.

Incoming Exchange Calls. In the directory listing of apartment house automatic systems, the telephone number of each apartment is divided into two parts, as for example, C5517—43 The first part of this number, namely C5517, pertains to the apartment house and the second part, namely 43, to the individual apartment, and where possible, coincides with the apartment number. In calling the apartment, whose telephone number is that just given, the subscriber calls the first five digits in the usual manner, and in so doing automatically selects an idle in-trunk to the apartment house switchboard, there terminating the partially completed connection upon the associated connector. The last two digits when called, cause the connector to select and ring the apartment whose telephone number is 43. For the information of the public, the telephone company maintains a record of names of the occupants of all apartments. In this manner, the information bureau of the telephone company removes the burden of inquiries from the management of the apartment house.

Calls to patrons living in family hotels may be made as above described where the full telephone number is known or can be ascertained. When direct calling is not convenient, the call may be made through the receiving cabinet, the telephone number of which is always listed. A call of this nature is indicated at the receiving cabinet by the burning of the lamp associated with the in-trunk involved in the connection. The attendant, in answering throws the associated answering key and is placed in direct communication with the calling subscriber, and after ascertaining the name of the party wanted, extends the call automatically to the proper station. When the called party responds, the answering key is restored to its normal position. This removes the attendant from any further control of the connection, which is released automatically when the calling subscriber hangs up. The attendant cannot listen on any completed connection, whether made direct or through the cabinet.

Incoming Calls from Local Telephones. The house, vestibule or tradesmen's telephones are not adapted to originate or receive exchange calls. Local calls to various apartments, however, may be made by calling on the dial, the two digits representing the number of the apartment wanted.

Pay Station Calls. All exchange calls to and from the pay station telephone may be received and made in the usual manner provided that on outgoing calls a coin is deposited before or after calling, depending upon the character of the coin machine. Both prepayment and postpayment automatic machines are in use.

COMMERCIAL AUTOMATIC PRIVATE BRANCH EXCHANGE

The first commercial private branch exchange of the automatic type installed in San Francisco, was placed in service May 27, 1911. Since that time 10 additional installations have been made. These 11 exchanges serve a total of 420 stations, an average of approximately 38 stations per exchange. The largest installation is 75 stations and the smallest nine stations. Each installation includes a portable automatic switchboard and storage battery similar to those placed in apartment houses. The switchboards, however, contain apparatus for local intercommunication as well as for in and out exchange service. A receiving cabinet, Fig. 4, adapted to receive and distribute incoming calls, which for one reason or another, are not made direct, is a necessary part of every commercial installation.

The salient features of the commercial automatic private branch exchange, may be briefly stated as follows:

1. Eliminates all operators and switchboard attendants, except those required for strictly information purposes, thus effecting a direct saving in operator hire either by eliminating the operator or by assigning her other duties.
2. Affords rapid and direct intercommunication between all local stations.
3. Affords direct " in " exchange service.
4. Affords direct and metered " out " exchange service.
5. The full value of the system is available 24 hours each day and every day in the year.
6. Instantaneous disconnection upon hanging up, thus permitting the making of a number of successive calls in the shortest possible time.

7. Each station is afforded the equivalent of direct main line service.

8. All connections, local and otherwise, are strictly secret.

9. Eliminates the necessity of other means of rapid intercommunication, now so common with manually operated private branch exchange switchboards.

10. Combines rapid intercommunication with regular telephone exchange service.

11. Automatic restriction of any station, to local service, thus preventing the abuse of outgoing exchange service.

12. But two wires are required per station, thus permitting the redistribution of telephones at a minimum cost. This point should not be overlooked when comparing the operating costs and flexibility of the automatic system with other systems requiring key buttons and other apparatus, necessitating the running of many wires to each station.

13. There is no limit to the size of any private exchange.

14. Any number of private exchanges may be interconnected and operated as one system, all, part, or none of which may have exchange service.

Description of Operation

Local Calls. In a commercial private exchange of a capacity not greater than 90 stations, any station may call any other station by calling on the dial, the two digits representing the number of the station wanted. Thus a station would call the digits 2 and 5 to effect a connection with station 25. The bell at the station called, rings until the call is answered or until the calling party hangs up in case the call is not answered. Should all " mechanical operators " or the called station be busy, the usual busy tone will be heard. A connection is released when the calling subscriber hangs up. Where the capacity of a private exchange system exceeds 90 stations, three digits must of necessity be called in place of two.

Outgoing Exchange Calls. To make an exchange call, the private branch exchange subscriber first calls the digit " 0 " to effect a connection with an idle out-trunk, and then the number listed in the directory. Should all out-trunks be busy, the busy tone will be heard as soon as the digit " 0 " is called. Each completed outgoing exchange call is registered upon a meter located in the central office and associated with the out-trunk involved in the connection. Calls to the telephone company's information and other departments, are not registered. Any local station may be restricted to local calling, that is, the station may not originate exchange calls, although it may receive exchange calls.

Incoming Exchange Calls. Incoming exchange calls may be made direct to any local station. To facilitate this, each local station, or such of them as the public may have occasion to call

PLATE VI
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[DEAKIN]
FIG. 1—PUBLIC TELEPHONE
Equipped with 3-slot
prepayment coin machine

[DEAKIN]
FIG. 2—HOUSE TELEPHONE FOR APARTMENT HOUSE SYSTEMS

[DEAKIN]
FIG. 3—HOTEL RECEIVING CABINET

[DEAKIN]
FIG. 4—COMMERCIAL EXCHANGE RECEIVING CABINET

[DEAKIN]
FIG. 9—PORTABLE STORAGE BATTERY

are listed in the directory. The directory number, as for apartment house systems, must consist of two parts, the first part indicating the private exchange as a whole, and the second part the local station number. Any call, which from the lack of information or otherwise, cannot be made direct to the proper local station, may be directed to the receiving cabinet, and when so directed causes a lamp associated with the particular incoming trunk involved in the connection, to light. The operator, when answering, throws an associated answering key and obtains such information from the calling subscriber as may be necessary, after which the call is automatically extended to the proper station. The answering key remains thrown during this operation and in fact until the operator has finished with the call. Should the operator find it necessary to transfer the call, she may release the local connection and then reëstablish it with another station. When the proper party has been located, the operator restores the answering key to its normal position, which places the calling and called subscribers in direct communication with each other and makes further supervision on her part unnecessary. The connection releases when the calling subscriber hangs up.

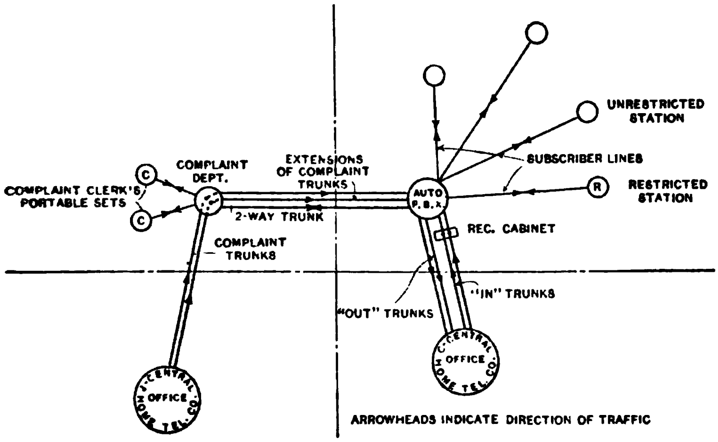

FIG. 5—LINE AND TRUNK DIAGRAM OF INSTALLATION NO. 15

Some Special Applications. The ease with which the automatic system may be adapted to meet special conditions, is indicated to some extent by the arrangements made to handle calls in installation 15. A line and trunk diagram of this installation appears in Fig. 5. The system comprises an automatic switchboard, a receiving cabinet and a plurality of special portable sets located in the complaint department, approximately one mile from the central offices. The complaint department and the general offices have different numbers, and so far as the public is concerned, are separate exchanges. Prior to the installation of this system, experience had shown that many complaints were directed to the complaint department which should have been directed to some department in the general offices. To handle such calls, the automatic equipment has been adapted to permit any misdirected call to be extended through the automatic private exchange switchboard to the proper department. The complaint clerks are merely required to call the two digits representing the station wanted. Similarly any call directed to the receiving cabinet may be transferred to the complaint department.

In another installation, four closely associated companies are served by the same switchboard. Each company has a separately listed receiving cabinet, but all make use of a common set of in- and out-trunks. Local intercommunication between the four companies is given on a two-number basis.

SWITCHBOARD EQUIPMENT

The individual pieces of automatic apparatus represent the latest development in switches of the Strowger and Keith types. A description of these switches as applied to central and sub-offices, will be found in the paper[2] by Mr. W. L. Campbell. To avoid repetition, mention is made here only of those features and adaptations which have especial reference to the automatic private exchange switchboard. To meet all demands, three sizes of switchboards have been developed with capacity for 25, 50 and 100 lines, respectively. The 25-line switchboard, Figs. 6A, 6B, 6C and 6D, is 21 in (51.3 cm.) square and 3 ft. 9 in. (1.13 m.) high. The 50-line switchboard, Figs 7A and 7B is 21 in. (51.3 cm.) square and 5 ft. 7 in. (1.6 m.) high. The 100-line switchboard, Figs. 8A and 8B, is 2 feet 8 in. (81 cm.) wide, 21 in. (51.3 cm. deep and 6 ft. 9 in. (2 m.) high. Each switchboard is a complete unit by itself and contains all apparatus necessary for its proper operation. The cabinets are fire-proof, dust-proof and as nearly moisture-proof as possible. It has been found that variations in temperature, at least those met with in San Francisco, do not materially affect the operation of the switches. Dust and appreciable moisture, however, make their presence

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[2] A. I. E. E. TRANSACTIONS, 1910, p. 55.

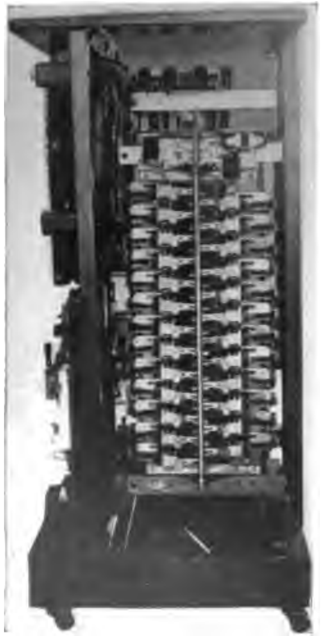
known at once. The charging circuit of some of the larger storage batteries, include one or more small resistance lamps. These, when placed in the cabinet, have proved effective in expelling moisture.

Each apartment house switchboard is equipped with a sufficient number of Keith line switches and service meters to provide one of each for each apartment. There is also provided a connector of the Strowger type for each in-trunk and for the house telephone. In the commercial switchboards, a line switch without service meter is provided for each station, a connector for each in-trunk and a sufficient number of " mechanical operators " to handle the local and out-trunk traffic. The relative locations of all equipment will be seen at a glance in the figures previously referred to. A 25-line board will accommodate eight large switches, a 50-line board 12 and a 100-line board 18.

The line switch banks in the apartment house switchboards, Figures 6A, 7A and 8A, are connected to two-wire out-trunks, which trunks terminate at the central office on primary line switches, and these in turn on secondary line switches and finally on first selectors. The act of removing the receiver from the hookswitch causes all three line switches to plunge in simultaneously. Each out-trunk circuit includes a train of relays, which relays, under certain conditions established as before mentioned, only when a certain number is called, are adapted to disconnect automatically the private exchange end of the out-trunk from connection with the central office apparatus and in place thereof connect it to the house telephone, Fig. 2. All line switch banks are multipled and each bank has capacity for 10 out-trunks, that is, each line switch has access to this number of trunks. Under ordinary conditions, one master switch controlling access to 10 trunks is sufficient. Should, however, the traffic be heavy enough in the larger boards to require more than 10 trunks, additional master switches may be added so as to provide as many as 10 out-trunks for each 25 line switches. The trunk connectors on the reverse side of the switchboard, Fig. 7B, are directly connected to two-wire in-trunks, which trunks at the central office appear in a multiple before the proper selectors. All apartment lines are multipled through the connector banks.

In commercial private exchange switchboards, the line switch banks, Fig. 6A, are wired to the " mechanical operators." The " mechanical operator," as it has been called for the lack of a better name, is a switch in which the functions of the selector and connector are combined. This switch operates as a connector in establishing two-number local connections. It supplies the necessary current for central energy speech transmission and automatically rings the call bell at the called station. When the digit " 0 " or other proper predetermined number is called, the switch is automatically converted into a selector and rotates automatically until an idle out-trunk is selected, after which it affords a clean pair of wires free from all bridged relays and other coils, for the transmission of the subsequent impulses. By a very simple change in line switch bank wiring, the switch restricts the local thus changed to local service. Should an exchange connection be attempted by a restricted station, the switch will release when the trunk " level " is reached.

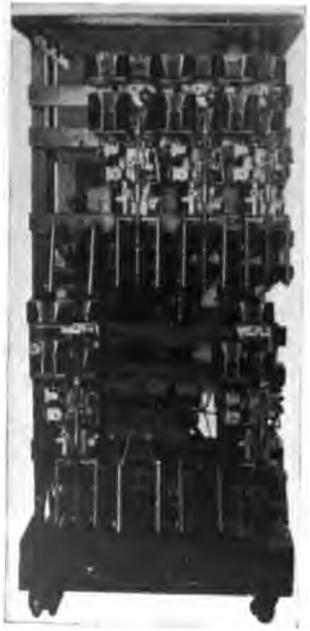
The development of the mechanical operator has greatly simplified the design of the commercial private exchange, in fact it has made the commercial private exchange possible, for without it, not only would the cost and size of the switchboard be increased, but local calling on two digits, a valuable asset of the present switchboard, would not be possible. The banks of the mechanical operators include a multiple of all local lines as well as a multiple of the out-trunks, which trunks are usually connected to the " 0 " level. The out-trunks terminate in the central office on line switches, as do those from apartment house installations. The in-trunks from the central office pass through a normally closed circuit in the receiving cabinet to the connectors, the banks of which are multipled with those of the mechanical operators. The in-trunk connectors may be provided with a "back release " whereby any connector may be released by either the calling or called subscriber. Such a release circuit makes it possible to transfer a call from one local station to another without requiring the calling subscriber to disconnect. The calling subscriber is merely required to call the two-digit number of the second station, after the station first called has hung up. This latter act causes the connector in the private exchange switchboard to release; the remainder of the connection in the central office, however, is not released until the calling subscriber hangs up. The receiving cabinet, Fig. 4, in each exchange is assigned some particular number, which, when called through a particular connector, results in the lighting of the lamp associated with that connector. The function of the receiving cabinet circuit is to release the connector from the connection with the receiving cabinet contacts and cause it to select, as directed, the bank con-



[DEAKIN]

Fig. 6A—Front Elevation of 25-Line Switchboard

Door removed, showing line switches



[DEAKIN]

Fig. 6B—Rear Elevation of 25-Line Switchboard

Doors removed, showing "mechanical operators," connectors and banks

[DEAKIN]

Fig. 6C—Side Elevation of 25-Line Switchboard

Doors removed, showing power panel, terminal strips and miscellaneous relays

[DEAKIN]

Fig. 6D—Elevation of 25-Line Switchboard

Doors in position. Meters shown protected by a glass plate

PLATE VIII
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[DEAKIN]

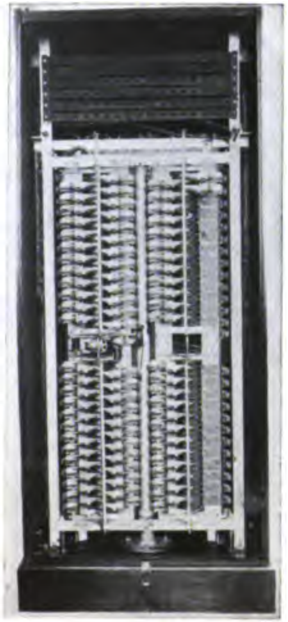
FIG. 7A—FRONT ELEVATION OF 50-LINE SWITCHBOARD

Doors removed, showing a partial equipment of line switches

[DEAKIN]

FIG. 7B—REAR ELEVATION OF 50-LINE SWITCHBOARD

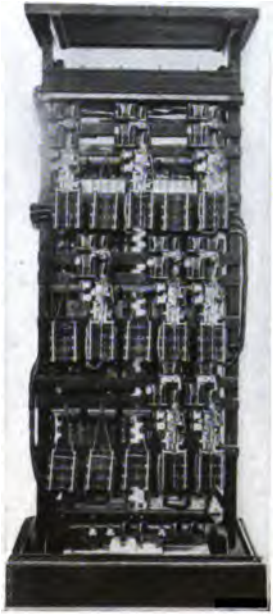
Doors removed, showing connectors and banks



[DEAKIN]

FIG. 8A—FRONT ELEVATION OF 100-LINE SWITCHBOARD

One door removed, showing line switches, master switch and service meter strips in position



[DEAKIN]

FIG. 8B—REAR ELEVATION OF 100-LINE COMMERCIAL SWITCHBOARD

Doors removed, showing the "mechanical operators," connectors and switch banks in position tacts of the desired station, leaving the circuit conditions, after the receiving operator has cut out, the same as if the call had been made direct from one station to the other. The noticeable feature about the receiving cabinet is its simplicity. No cords, plugs or jacks are required, merely two keys and a lamp for each in-trunk.

One hundred lines is by no means the limit of the automatic private exchange. Beyond this limit, however, the use of three or more digits is necessary. The switchboard cabinets have been designed with a view of permitting them to be lined up and operated as one switchboard, a condition always to be met in office buildings.

Each switchboard is wired and arranged for over-flow meters installed from time to time, to determine the sufficiency of the facilities provided. Three meters are required for commercial installations, one adapted to record the attempts made to call when all mechanical operators are busy, another the attempts made to call when all out-trunks are busy, and another the attempts made to call when all in-trunks are busy. Meters are also provided to register the total in, out and local calls. Commercially, the ability to take such readings is of great value to the telephone company as it affords something definite to offer the subscriber as an argument why inadequate facilities should be increased. Each board is assembled and tested before leaving the shop so that the labor required to install one of them is not much greater than that required to install the corresponding manual switchboard.

CURRENT SUPPLY AND SUPERVISION

The source of direct current required for the operation of an automatic private exchange switchboard and for central energy speech transmission, must afford a fairly uniform and constant potential, a condition not so essential for the proper operation of a manually operated private exchange switchboard. It must also be capable of supplying comparatively large currents for short intervals, for the intermittent operation of the motor and release magnets, some of which require as much as an ampere and a half. It is quite possible that the simultaneous operation of a number of switches might result in a call for five or six amperes, which, in telephone private exchange work, is considerable. These currents, however, are required for periods on the order of a second, and therefore, do not involve much energy. Intermittent currents of this nature tend to reduce the potential of the supply at the switchboard busbars and make the speech transmission circuits noisy, and therefore must be taken into consideration as a factor in determining the character of the current supply. It has been found that automatic switches can be adjusted to operate positively within a range of potential varying from approximately 45 to 55 volts, providing that all switches are adjusted at normal potential of 48 to 50 volts.

The foregoing requirements have all been satisfactorily met by installing small portable storage batteries within a few feet of each switchboard. These batteries each consist of 23 elements contained in rubber jars, the whole mounted in a substantial oak carrying case, with the intervening spaces filled with an insulating and acid-proof compound so that should a cell become cracked, the electrolyte will not escape. Such a battery is shown in Fig. 9. The case is made nearly fume-proof, so as to permit the battery to be placed, without objection, in an office or other occupied quarter. Each battery is given its initial charge in the warehouse or shop, which, together with the fact that the terminals are brought out to end cell switches, permits the immediate installation of the battery upon delivery. The end cell switches are used chiefly as a means of obtaining the normal potential when adjusting switches. Intermittent charging of a storage battery results in high and low potential values. To eliminate such variation as far as possible, the batteries are floated on approximately constant currents, which currents are adjusted to

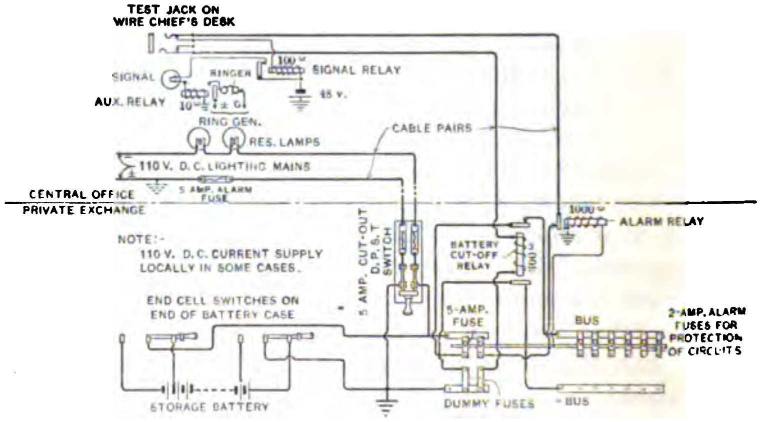


FIG. 10—CURRENT SUPPLY AND SIGNAL CIRCUITS

meet the 24-hour requirements of their respective installations. Providing the floating or charging current is made sufficient, the smallest size of commercial battery can be made to handle the largest exchange. From the standpoint of economy, however, the capacity of the battery should be such as to permit it to handle the peak loads of the exchange, without requiring an increase in the normal day and night floating currents, in case the two are not the same, to prevent a serious drop in potential. From the information available at the time the first installations were made, it was calculated that economical results could be obtained by the use of batteries having the following ampere-hour capacity. The results obtained to date have been very satisfactory and so far have not warranted other assumptions.

Total in, out and local calls per working day	Capacity of battery
400	6 ampere-hours
800	12 " "
1600	24 " "
2400	36 " "

The foregoing figures allow for contingencies in the way of abnormal traffic and trouble.

The current supply and signal circuits of a typical installation are shown in Fig. 10. It will be seen that the storage battery receives its charging current from the city 110-volt direct-current lighting mains, which current may be supplied locally, or as is preferable, over an idle cable pair from the nearest central office. When supplied in this latter manner, the current may be regulated with ease. The circuit affords the wire chief at the central office complete supervision of the power supply and a ready means of obtaining voltage readings. All important pieces or groups of pieces of automatic apparatus on each private branch switchboard are served by separate fuses of the alarm type. The fuses are of low capacity, so that should a switch stick, or otherwise permanently close a low-resistance circuit through some motor magnet, or create a short circuit, the corresponding fuse will blow and give the alarm at the central office. The wire chief, by the proper manipulation of his testing circuit, not shown in the figure, may remove the current supply from the switchboard and in this way often release a sticking switch. Furthermore, the guard relay at the central office is adjusted to operate should the difference in potential between the private exchange and central office batteries exceed three volts.

The curves plotted in Fig. 11 show the potential variation at the switchboard terminals, of two six-ampere-hour batteries, for a period of seven months. The average continuous charging current in each case was approximately 0.1 of an ampere. It will be seen that in no case did the potential vary beyond the limits previously given. The voltage readings of all batteries are taken and recorded at 8 o'clock every morning and the curves just mentioned are plotted from these readings. These curves may be applied to all apartment houses without serious error and to other installations where the volume of daily traffic is more or less constant. The traffic, however, in most commercial installations, originates almost entirely between the hours of eight in the morning and six in the evening, and on working days only.

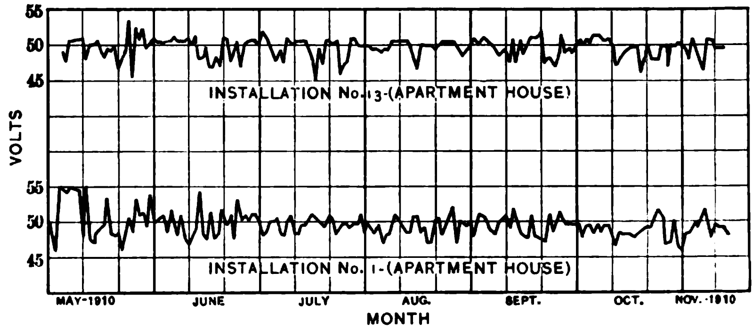


Fig. 11—Potential Variations of Two Small (6 Ampere-hour) Storage Batteries
Average charging or floating current, 0.1 ampere

At other times, the traffic is almost negligible. This condition is very clearly illustrated by the potential curves, Fig. 13, which apply to a 24-ampere-hour battery serving a large commercial installation, handling approximately 1250 calls of all classes per working day. In this particular case, the best results were obtained by adjusting the continuous charging current during working hours, to from 0.5 to 0.8 of an ampere, and during nights and holidays to from 0.1 to 0.3 of an ampere. Both these and the following curves are plotted from readings taken at 15-minute intervals. The potential curves shown in Fig. 12 apply to a storage battery installed to take care of an automatic switchboard in a large newspaper establishment. Here the best results were obtained by floating the battery continuously on a current of approximately 0.35 of an ampere. This is one of the compara-

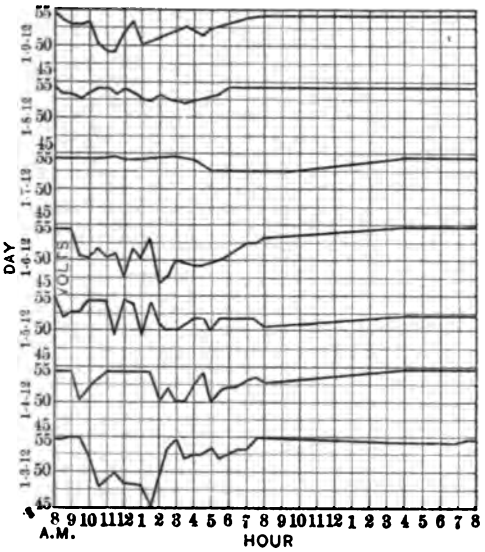


FIG. 12—POTENTIAL VARIATIONS OF A 12-AMPERE-HOUR STORAGE BATTERY

Installation No. 21; charging current 0.35 ampere

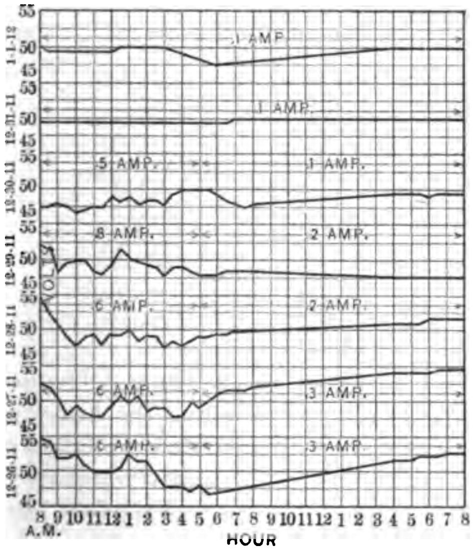


FIG. 13—POTENTIAL VARIATIONS OF A 24-AMPERE-HOUR STORAGE BATTERY

Installation No. 15; charging current indicated tively few commercial installations in which the traffic is considerable during the night hours.

The routine adhered to in maintaining these small and isolated batteries, is to record their voltage readings at the central office daily and to take the specific gravity of the pilot cell once in every two weeks and the specific gravity of each cell once in every two months. This plan does not involve any great amount of labor, but it effectively prevents the condition of any battery becoming serious, without ample warning. The particular battery used in the installation handling the heaviest traffic, has been in service five years. Prior to its installation in its present location, it was used by the construction company, for a similar purpose, during the building of the independent telephone plant in San Francisco.

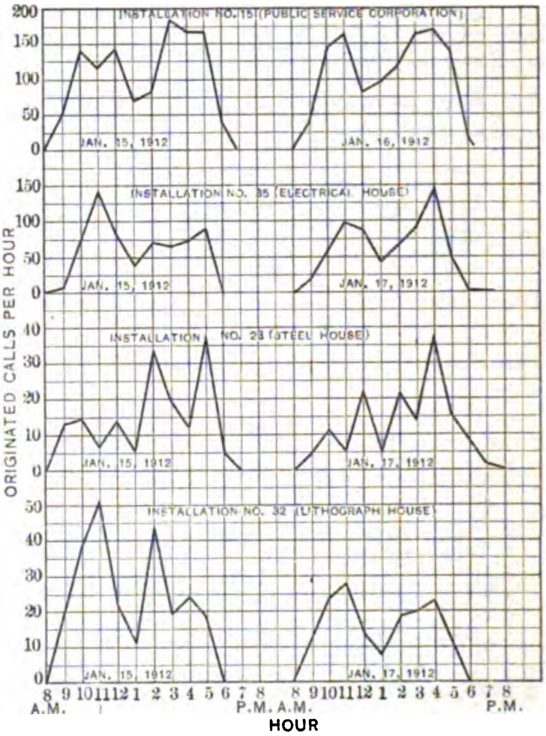


FIG. 14A—HOURLY TRAFFIC—ORIGINATED CALLS

SOME TRAFFIC DATA

Local calling, in the commercial exchanges, affords some interesting data regarding the capacity of the mechanical operators to handle a heavy traffic. While these installations are limited in number, they are, however, all made in representative organizations, which, for the most part, are among the largest and most important of their kind. The hourly traffic of five installations is graphically shown in Figs. 14A and 14B. Curves for the same installation, but for different days, show an unexpected similarity. It will be seen that the traffic of installation 21, a large daily newspaper, continues pretty well through the night, in fact the busy hour is so included. On the other hand, the traffic of the remaining installations originates almost entirely between the hours of eight in the morning and six in the evening.

A total of three hundred or more observations were taken at seven of the commercial installations in order to determine the average length of conversation and the speed of operation on local connections. The average results in seconds for each installation are given below.

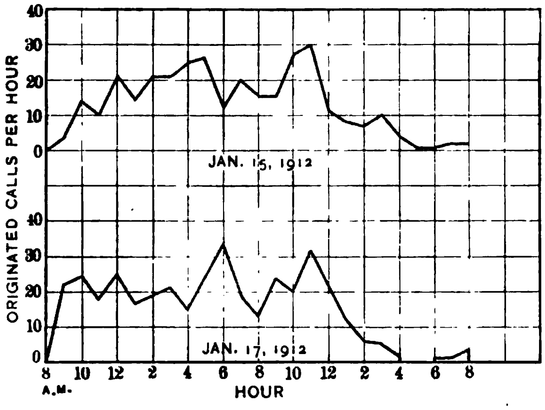


FIG. 14B—HOURLY TRAFFIC—ORIGINATED CALLS
Installation No. 21, newspaper office

Installation number	To call	To answer	Talking	Total
15	2.17	10.	59.6	71.77
19	2.2	7.2	62.4	71.8
21	2.2	10.4	54.2	66.8
30	1.9	11.	33.5	46.4
31	2.0	9.7	54.5	66.2
32	1.8	12.	32.1	45.9
35	2.4	7.7	41.5	51.6
Average	2.1	9.7	48.2	60.0

In the second column of this table is given the elapsed time between the removal of the receiver, as indicated by the plunging in of the line switch, and the selection of the line called, as indicated by the stepping of the side switch of the mechanical operator into its third or final position. The average time required to answer is given in the next column, and in the next two columns, the average length of conversation and the total elapsed time, respectively. It will be seen that the average time required to establish a connection between the calling and called lines is but 2.1 seconds. Compare this with 3.5 seconds, the average time required by an " A " operator in a well maintained manual system, to answer a call under normal operating conditions. This latter figure, furthermore, applies to central offices of the most modern type, and it will be admitted without argument that the average time of answering in manual private exchanges, in which heavy overloads are frequent, is much longer. From these remarks, it will be seen that it takes less time to establish a local connection in an automatic private exchange system than is required by an operator to even answer a call in a manual system.

The following represents the average performance of the mechanical operators of installation No. 15, a typical traffic curve for which is shown in Fig. 14A.

Number of mechanical operators.........	8	
Number of stations....................	75	
Originated calls per working day.........	1150	
Average rate of calling per station per working day.......................	15.3	
Originated calls, busy hour...............	180	
Ratio, busy hour, to entire day..........	15.5	per cent
Originated calls per mechanical operator per busy hour.......................	22.5	
Originated calls per month of 26 days.....	29,900	
Average overflow calls per month,........ (Average for 4 months, minimum 181, maximum 285.)	230	
Ratio of overflow to originated calls......	0.77	per cent
Total originated calls per year...........	359,000	
Total calls per mechanical operator per year................................	45,000	

Sufficient data have not yet been obtained to determine with any degree of accuracy the capacity of the in and out automatic trunks. The number of trunks in commercial installations is more or less arbitrary, and depends upon how many the subscriber is willing to pay for. In apartment house installations, two out- and one in-trunk have been provided for 25-line installations and two out and two in for 50-line installations.

Some First Costs

The first costs of apartment house automatic switchboards placed in position, ready for operation, are shown in Fig. 15, curve *A*. These costs include all factory and shop labor and material, storage battery, all miscellaneous power wiring and the installation labor and material necessary to place the boards in actual service. The corresponding costs of commercial automatic private exchange switchboards are shown by curve *B*. The first cost of apartment house and commercial telephones installed are shown by *C* and *D* respectively; the former includes in addition to the telephone, installation labor, but not wire. The commercial telephone costs, curve *D*, include both installation labor and wire. The summations of these first costs of apartment house and commercial installations are given by *E* and *F*, respectively. The switchboard costs refer to locally-made boards, in the manufacture of which high-priced day labor was used. It is, therefore,

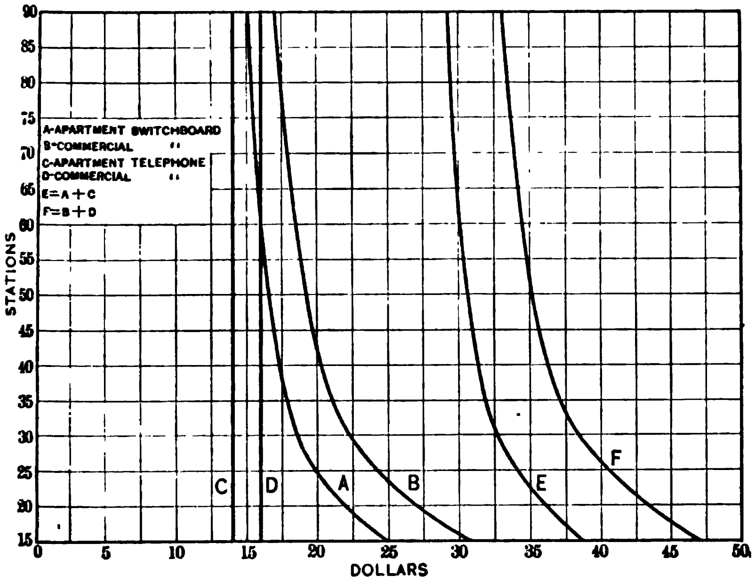


Fig. 15—First Costs per Station—Automatic Installations

reasonable to assume that a considerable reduction in these costs could be made were the boards to be manufactured in a large factory especially adapted for the purpose.

The corresponding costs of manual private exchange installations are shown in Fig. 16. The first costs of apartment house and commercial switchboards, curves *A* and *B* respectively, include the switchboards installed and connected, ready for immediate operation. They do not, however, include storage batteries, since the majority of such boards obtain their current supply from the nearest central office over a group of cable pairs. The first costs of apartment house and commercial telephones installed, are shown by *C* and *D*, respectively, and the total costs of complete installations by *E* and *F*, respectively. In the preparation of these costs, the prevailing prices of the so-called independent manufacturers of telephone apparatus were used.

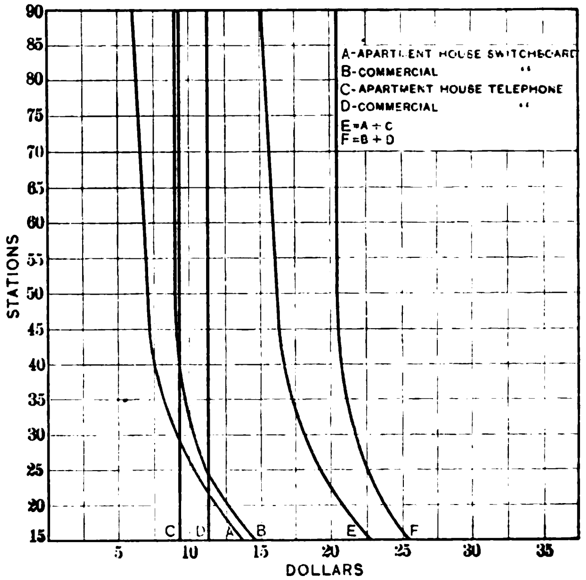


FIG. 16—FIRST COSTS PER STATION—MANUAL INSTALLATIONS

Neither Figs. 15 or 16 include any central office costs, overhead charges, underground or aerial cable costs, nor the cost of the lateral into the building and its associated main terminal.

A comparison of the costs shows that for the largest installations the automatic system is approximately 60 per cent more costly than the manual system, and for the smallest installation 85 per cent more costly.

SOME ANNUAL COSTS

Item 1. *Maintenance Labor.* Up to the present time, data collected from 26 installations show that the average labor cost of maintaining commercial automatic private exchange installations, both switchboards and telephones, is approximately $3.00 per station per year, and of apartment house installations, $1.18 per station per year. The Bay Cities Home Telephone Company operates, in addition to the automatic private exchanges, a large number of manual private exchanges. From the data afforded by these installations, it is estimated that the average labor cost of maintaining commercial manual installations, exclusive of calling device trouble, is approximately $1.50 per station per year, and of apartment house manual installations, $0.60 per station per year. None of these figures include overhead charges and supervision, nor do they include the cost of operating and maintaining the central office plant and the underground and aerial cable systems. The difference between the charges for the commercial and apartment house installations may be attributed to the fact that the traffic, with the resulting wear and tear, is much heavier in the commercial installations.

Item 2. *Depreciation, Interest and Taxes.* The average life of manual private exchange switchboards, is considered, I believe, by the Bell companies, to be approximately 10 years, which would make the depreciation of this class of equipment 10 per cent. This comparatively short life is due to the fact that the switchboard is exposed to extremely rough and severe usage. The items which receive exceptionally hard service are the highly finished cabinet, plugs, cords, jacks and keys. Much of the latter equipment is soon broken and worn beyond repair. The refinishing of a cabinet for a new or re-installation is costly. The automatic switchboard, on the other hand, includes a practically indestructible metal framework, which affords complete protection to the automatic apparatus located within. This apparatus contains no parts which, when worn out, require the replacement of the whole. Those parts subject to wear are not costly and are easily replaced, and in fact are replaced as part of the regular maintenance work. Furthermore, automatic apparatus is not handled in the sense that manual apparatus is handled, which permits the wear and tear to take place in the parts designed to allow for such wear and tear. From these remarks it would seem reasonable to assume that an automatic switchboard will outlast a manual switchboard to a considerable extent, and in this paper a depreciation charge of 8 per cent will be used. The necessity for even this charge is primarily to provide for changes in the art which may require the replacement of the switchboards or parts of them, before they are actually worn out. Including average interest at 3½ per cent and taxes at 1½ per cent, it will be seen that the total of the three items in question, for automatic and manual switchboards, is 13 per cent and 15 per cent respectively.

Depreciation, interest and taxes on telephone apparatus has been taken at 17½ per cent for both automatic and manual. The figures previously given allow for an increase in the maintenance of the automatic telephone to care for the calling device.

Item 3. *Current Supply and Miscellaneous Costs.* For a year of 312 working days, it can be shown from direct meter readings that the average cost of power consumed in commercial automatic installations at 4 cents per kw-hr., by one call per day for one year, is 2.5 cents. It may also be shown, on the basis of a year of 365 days, that the annual cost of the power consumed in an apartment house automatic installation at 4 cents per kw-hr. by one call per day, is approximately 5 cents. The difference between these two figures may be attributed to the fact that in the latter system considerable power is wasted in maintaining the batteries in their proper condition. In addition to the cost of power consumed, each installation must be charged with the annual cost of four cable pairs, one for charging, one for the busy tone and ringing interrupter, one for ringing power, and one for supervision. The average length of cable circuit is estimated at one half mile, which at the present time conforms very closely to the actual conditions prevailing in San Francisco. The total annual cost of No. 22 B. & S. gage cable including all charges is taken at $3 per pair per mile, which makes the total annual cost of the four pairs $6.

Power for manual private exchange switchboards, within a radius of one half mile is almost invariably supplied from the nearest central office storage battery over a group of cable pairs. Within this limit, such an arrangement is nearly always the most economical. The average power consumed per connection, by the manually operated private exchange switchboards of the Bay Cities Home Telephone Company, is 0.1 watt-hr., and with power at the storage battery busbars at 5 cents per kw-hr. amounts to approximately 0.156 cents per year, for one call per day—a negligible amount. Since the size and cost of feeders depend upon the average maximum instantaneous current requirements, it is essential that the ratio of the busy hour to the entire day be known. Here the ratio of 15.5 per cent, derived from the data afforded by installation 15, will be taken. This is somewhat lower than the ratio met with in most private exchanges, and therefore favors the feeder method. Upon this assumption it can be shown that the annual cost of a feeder, one half mile in length and serving a manual private exchange switchboard of the type used by the Bay Cities Home Telephone Company, is approximately 1.63 cents per call per day.

In addition to these two costs, each manual installation must be charged with $1.50 as the annual cost of the cable pair supplying ringing generator current.

Item 4. *Operating Costs.*

Automatic Apartment House Systems. No operator required.

Commercial Automatic Systems. In, out and local calls are assumed equal. This at once eliminates the operator from two-thirds of the total calls. It is estimated that 80 per cent of the remaining in-calls will be made direct, which leaves but 6.7 per cent of the total calls to be handled by an operator. The few calls of this nature, in most installations, may well be handled by a clerk who has other duties to occupy his or her full time. Upon the assumption that the average salary paid such a person is $45 a month and that with full time devoted to operating, 500 calls a day can be handled, it will be seen that the cost of handling each call is 0.35 cent.

Apartment House Manual Systems. The rate of calling is not a controlling factor in determining the cost of operator hire in apartment houses served by manual switchboards. The quality and extent of service is largely dependent upon the management. The more pretentious apartment houses generally give the more extensive and therefore more costly service. The following schedule is based upon observations made in and around San Francisco.

30 apartments or less, one day operator at $35 per month. Evening service given by proprietor, janitor or elevator boy, as the case may be.

31 to 50 apartments, one day operator at $35 and one night operator to 10 p.m. at $20, a total of $55 a month.

Above 50 apartments, one day operator at $35 and one night operator to 12 p.m. at $35, a total of $70 a month.

Commercial Manual Installations. Data collected in San Francisco show that the full time of an operator is required for private exchange work when the number of all classes of connections handled per day is between 500 and 1000. With less than 500 calls an operator may devote her spare time to other duties.

It is estimated that $45 is a fair salary for a first-class commercial private exchange operator. This sum, however, is less than the average received by operators in San Francisco, concerning whom information has been obtained.

Comparison of Annual Costs

Corresponding annual costs of automatic and manual private exchanges are given in Fig. 17. Those costs pertaining to commercial installations apply in particular to exchanges equipped to handle a total of approximately 20 in, out and local calls per station per day. Two in and two out calls per station per day are provided for in the costs of the apartment house installations.

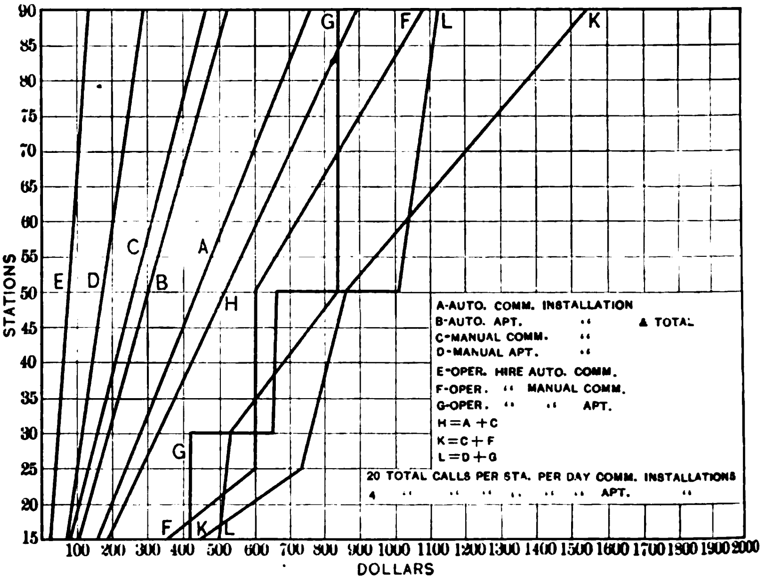


Fig. 17—Comparative Annual Costs

Curves *A* and *B* represent the summation of all costs included in items 1, 2 and 3, for commercial and apartment house automatic installations respectively. Curves *C* and *D* represent the corresponding costs of manual installations. The costs of operator hire, item 4, in commercial automatic installations, are given by *E*, and in commercial and apartment house manual installations by curves *F* and *G* respectively. Curve *H* gives the total annual costs of commercial automatic installations including operator hire. Curves *K* and *L* give, respectively, the corresponding costs of commercial and apartment house manual installations.

The most striking feature in the results set forth in Fig. 17 is that the cost of private exchange operator hire alone, in manual installations, is greater than the total annual cost of operating and maintaining automatic installations. Considering the total costs of each it will be seen that the annual costs of the manual system are from 70 per cent to 300 per cent greater than the annual costs of the automatic system. Eliminating operator hire, the annual cost of the automatic system is from 60 per cent to 90 per cent greater than the manual system.

RECAPITULATION

In the foregoing pages, an attempt has been made to show that the automatic private branch exchange is practicable and economically possible. The pertinent questions still unanswered are these. Do the advantages claimed for it, justify its general installation in commercial organizations and apartment houses in preference to the manually operated private exchange, and is automatic equipment reliable? The answer to the first question will be found in a further discussion of some of the distinguishing features of the automatic private exchange.

The elimination of or reduction in operator hire, made possible by the installation of automatic equipment, results, as has been shown, in a saving, more than sufficient to pay for the entire cost of maintaining an automatic exchange. The complete elimination of the operator from apartment house installations might be objectionable were it not possible to make use of the information bureau, a department maintained by every telephone company. The results obtained in San Francisco show that the increase in cost of operation necessary properly to handle information calls for the occupants of apartments, is negligible. Where the period of occupancy is more than a few months, " extra listing " in the directory affords the tenant the equivalent of main line service in every respect. The substantial elimination of the private exchange operator by the installation of automatic private exchanges affords the telephone company an additional source of revenue—an opportunity which should not be overlooked—for it has been shown that the maintenance and first costs of automatic exchanges are materially higher than manual exchanges, thus permitting higher rates with a saving to the subscriber and a greater return to the telephone company for a given number of stations.

Anyone who uses or has used an automatic private exchange for local intercommunication must realize the advantage this system has, in this respect, over the old. Local calling differs somewhat from exchange calling in that the numbers of the locals to which the majority of calls are made can be easily memorized, or at the most, placed on a slip of paper easily reached, thus making the effort required in calling, little more than that required to depress a push button to call the office boy. With reference to exchange calling, it is sometimes argued that patrons of manual private exchanges prefer to have the private exchange operators obtain numbers for them, rather than ask for a trunk to the central office and obtain the number for themselves, and that the automatic private exchange is wanting in this respect. This practise of indirect calling in manual systems is now quite generally followed throughout the country, even though the telephone companies discourage it as much as possible. The argument in favor of this practise, from the calling subscriber's viewpoint, is that he would otherwise have to repeat his instructions to at least two operators, and in case the call were for another private exchange subscriber, to three operators, with a possibility always of from one to three delays. The calling subscriber, therefore, can hardly be blamed for placing the burden of such calls upon the private exchange operator, when one is available. The subscriber who receives such a call, however, has a somewhat different viewpoint even though he may be guilty of the practise himself, when calling, for he is asked his name by the operator and then politely told to hold the line while she calls the first subscriber back on the line. It quite often happens, particularly if there is a delay in getting a party, that the calling subscriber engages in other work and does not answer the call promptly. This naturally tends to irritate the subscriber who has been called. From any viewpoint it must be admitted that even if direct calling is burdensome, it is an imposition to place the burden upon the called subscriber. In comparison with this tedious and indirect method made necessary by the introduction of manually operated private exchanges into manual exchange areas, it is well to note that the introduction of automatic private exchanges into automatic exchange areas does not require a change in operating methods; the subscriber is merely required to call from one to three additional digits, each requiring, on an average, an addition of one second to the calling time. Other than this the subscriber handles the call in every detail as though it were being made from one main line to another. Patrons of main line manual service, and of the well-known multi-key intercommunicating private exchange service, do not object to getting numbers themselves. It is, therefore, reasonable to assume that patrons of manual private exchange service would likewise not object, providing the introduction of the manual private exchange did not introduce additional delays and more cumbersome operating methods. To illustrate more clearly the simplicity of calling in the automatic system and the multiplicity of indirect calling in the manual system, in both cases from and to a private exchange, I beg to call attention to the following tabulation in which the time required by the different stages of the calls is given. The figures with reference to speed of operation in the manual system represent the average of good service in a large, well maintained multi-office exchange. It has been assumed that private exchange and central office operators are equally efficient, a condition not realized in actual practise. I believe that not even the most ardent advocate of the manual system will disagree with me when I say that at least 15 per cent of the total originated calls in any well run manual exchange require from 4 to 12 seconds or more to answer. If this is so, a correspondingly greater number of delays must be expected when three operators are involved. All delays of this nature are eliminated by the automatic system.

	Automatic system	Manual system
Calling number, 8 digits	8 sec.	
Answering first P. B. X. operator		3.5 sec.
Giving instructions and making connections		8.5 "
Answering " A " operator		8.5 "
Making connections in central office (80 per cent trunking)		13. "
Answering second P. B. X. operator		3.5 "
Giving instructions and making connections		8.5 "
Answering subscriber (from preceding traffic data)	9.7 sec.	9.7 "
Ringing and answering of calling subscriber		3.5 "
Conversation (from preceding traffic data)	48.2 "	48.2 "
Disconnection P. B. X. operator		3.5 "
Disconnection " A " operator		3.5 "
Total elapsed time	65.9 sec.	108.9 sec.

Upon the assumptions given it will be seen that the total time involved in a connection through the manual system is 65 per cent greater than in a connection through the automatic system. It will also be seen that in the latter system the subscriber is required to wait but 17.7 seconds for an answer as against at least 50.2 seconds in the manual system. Furthermore, in the automatic system, the busy tone, in case the line called is busy, is obtained in eight seconds, whereas 45 seconds must elapse before a similar report can be obtained through a manual system.

Even though the indirect method of calling is not deemed necessary in an automatic system, it can, however, be provided for where conditions require, as is illustrated by the special arrangements made in one installation, whereby the clerks of certain officials establish the outgoing exchange connections and answer the incoming exchange connections. The local calls, only, are originated and answered by the officials. The desired result is obtained by placing two ringers on each line, one at the clerk's desk, adapted to ring on incoming exchange calls only, and the other on the official's desk, adapted to ring on local calls only. Secrecy is afforded by causing the clerk's telephone to be automatically cut off when the official is using the line. The circuit is further adapted to permit the official and clerk to converse with each other without being overheard by a calling party.

Secrecy on all connections, instantaneous disconnection upon hanging up and the fact that the full value of the service is available 24 hours each day and every day in the year, are all arguments for the automatic private exchange.

Proponents of the manual system have always put forth the argument that subscribers, as a whole, object to the fundamental principle of the automatic system, which requires them to call numbers with a dial or other calling device. Actual investigations, so far as I have been able to ascertain, have never substantiated this statement. In fact, I believe such investigations as have been made in cities where an automatic system is in proper operation, show that the public as a whole prefers this system to the manual. It will be admitted that there are many people whose time is so valuable that it may not be wasted. Such people, however, are nearly always provided with an ample force of clerks upon whom the burden of calling may be placed, whether it be in a manual or an automatic system.

Calls for toll or long-distance service from an automatic or in fact any private exchange, must be checked by some responsible party, if abuse of this service is to be prevented. In San Francisco an automatic private exchange subscriber calls the toll opperator in the usual way, which operator in establishing the connection refers the call back to the receiving cabinet operator, who takes note of it and extends the connection to the originating station. Correspondingly simple methods have also been worked out to handle " two-number " business without delay.

It was not without some apprehension that the first automatic private exchange installation was made. Many doubts were expressed as to its reliability and its ability in general to give service without undue cause for complaint. It was known, as stated in the first part of this paper, that the unattended sub-office was a success, but the extreme smallness of the unit, the inability to control the surrounding conditions with regard to temperature, dust and moisture, and the non-uniform potential of the current supply, were all unknown factors, each capable of seriously affecting the operation of the switchboard. The success, however, of the first installation immediately caused this feeling of doubt to give way to one of confidence, which feeling was further augmented by the fact that the apparatus used was primarily not intended for the purpose to which it was put. The untold possibilities for improvement in the design and manufacture of automatic apparatus, so as to decrease the cost of maintenance, is, I believe, at least one feature that assures the future of the automatic private exchange.

The final test of any public utility is its ability to satisfy the public and from this viewpoint the automatic private exchange has not been found wanting. A complete record of all complaints received from all sources is kept by the Bay Cities Home Telephone Company. During the operation of installation 15, which covers a period of eight months, 173 complaints were received, resulting in 221 recorded cases of trouble and comments, which, together with the record of installation 21 for four months, are given here in detail.

Complaints from installation 15 average one for each 1400 originated calls and from installation 21, one for each 1480 originated calls. During the entire year of 1911, 29 complaints were received from apartment house installation 1, an average of one for each 450 outgoing calls. These complaints might easily be a serious matter were their nature such as to interfere with the service of the installations as a whole. An examination of all records does not reveal a single case where an entire switchboard was put out of service. On the contrary, substantially all trouble affected but one line or one trunk. The foregoing records of installations 15 and 21 show that the actual private exchange switchboard trouble was but 4 per cent greater than the trouble due to broken and bent station apparatus, caused by rough handling on the part of the subscribers. One station of installation 15 shows a record of three new receiver shells in one month. Of the 173 complaints received from installation 15, all were recorded O.K. within 11½ hours, 94 per cent within 6 hours, 80 per cent within 3½ hours, 70 per cent within 2 hours, 45 per cent within 1 hour and 11 per cent within 15 minutes—which 11 per cent includes all of the more serious troubles, such as a sticking switch or a blown fuse.

Character of trouble	Installation No. 15		Installation No. 21	
	No. of cases	Per cent of total	No. of cases	Per cent of total
C. O. Switchboard	2	0.9	none	
P. B. X. "	43	19.4	15	24.2
Calling device	50	22.6 }	6	9.7 }
Broken & bent station apparatus	35	15.85 } 54.3	13	21.0 } 45.2
Other station apparatus trouble	35	15.85 }	9	14.5 }
Inside wiring	1	0.45	1	1.6
U. G. Cable	none		none	
Misuse	3	1.35	none	
Slow to answer	5	2.3	2	3.2
Don't answer	5	2.3	1	1.6
O. K. on test	42	19.0	15	24.2
Total	221	100	62	100

A manual private exchange switchboard is built primarily to accommodate an operator. The automatic private exchange switchboard, on the other hand, is built to facilitate the up-keep of the apparatus located within it and may be opened for inspection at any time, without inconveniencing anyone. A manual switchboard can rarely be got at during working hours, without seriously inconveniencing the operator, which makes the remedying of the fault more difficult and costly.

The automatic private exchange may with slight modifications be readily adapted to manual exchange areas. In such areas it would afford direct intercommunication and direct out-going exchange service. Obviously, all incoming calls would have to be made through the receiving cabinet, unless the central office operators were provided with a means of calling, concerning which a word will be said later. It will be seen at once that a reduction of at least 66 per cent in operator hire can be made in commercial private exchange installations by using automatic equipment. A further reduction should be possible, since the automatic system does not require supervision on the part of the attendant after a connection has once been established. · In apartment houses, the services of a telephone operator could in many cases be dispensed with by placing the small receiving cabinet in the elevator where it may be looked after by the elevator boy. At first thought it might appear that a cabinet so located would seriously affect the quality of service. With proper design and supervision, however, this need not be the case, since the elevator boy would be required to do nothing more than to extend the call to the proper apartment. Should the line called be busy the busy tone will be automatically given to the calling subscriber, and should the party fail to answer, the continuous recurrence of the ringing interruptions now well understood by the public, although they have never been mentioned in any instructions, would indicate that the party called does not answer.

An automatic private exchange switchboard can easily be adapted to serve any number of exchanges within its capacity; for example, a 90-line board could be installed in an office building and adapted to serve nine 10-line installations or it could be installed in some one apartment house and adapted to serve six 15-line installations. With a switchboard so arranged, it would also be possible, where a number of small apartment houses or flats are erected within the same block, to place a receiving cabinet in some one apartment house and allow it to serve all houses, the proprietors of the different houses sharing the expense.

In many cities a general demand has been made of late by apartment house proprietors and owners for a service which does not require apartment house operators or attendants. This demand has been met in manual exchanges to some extent, by installing, in each apartment, main or party lines equipped with coin machines. Such service is obviously costly where any great amount of cable is involved and has the objection that many people do not want coin machines or party lines, and furthermore, requires much space on the main switchboard for which the return is not always adequate. All these objections, can, I believe, be overcome by the installation of automatic private exchanges, for by so doing the telephone company could place in the central offices, operators provided with special equipment adapted to operate such switchboards, and by the proper adjustment of rates could place, and rightly so, the burden of the additional operators upon the houses they serve. The cost of service under such an arrangement, particularly to the small apartment houses, would be very much less than it is now with a separate operator in each establishment, and, by confining the operators to the central offices, 24-hour service would be possible, a point not to be overlooked as an argument for higher rates. While it may be economical to substitute central office operators in this manner in a manual exchange for apartment house operators, such a course would not necessarily be the proper one when applied to commercial private exchange installations, for in nearly all such installations, the operator, as before stated, may be assigned other duties, and in this way, his or her full time used to the best advantage, a condition not possible in apartment houses, where other work cannot be found for an operator.

While the automatic private exchange may be considered a success in the larger cities and towns, the development of automatic apparatus in general has not yet reached the stage where it may be placed in localities which cannot afford ample skilled labor to look after it. Automatic equipment, like a watch, need not require much attention, but when attention is required, quality and not quantity should be considered. It should not be inferred from this that skilled labor is hard to get in the larger cities, for if San Francisco may be taken as an indication of what may be expected elsewhere, it is not. The work is interesting and ambitious men take to it readily. There are, no doubt, many other conditions under which the automatic private exchange is not yet fitted to give the best service, but the installations referred to in this paper demonstrate, I believe, beyond a reasonable doubt, the ability of the automatic private exchange to serve satisfactorily the average commercial organization and apartment house in a more economical manner than is now possible with the manually operated private exchange.

DISCUSSION ON "AUTOMATIC PRIVATE BRANCH EXCHANGE DEVELOPMENT IN SAN FRANCISCO" (DEAKIN), PORTLAND, ORE., APRIL 17, 1912.

H. M. Friendly: I ask if Mr. Deakin has ever considered the use of a private branch exchange having a limit of 171 stations, instead of the 90-station limit, in order to obviate having to use second selectors. In Chicago, I saw a 190-line connector-switch the manufacturers had designed, but I have no knowledge of its practical use. I also saw one at Columbus, Ohio, that they were testing. The switch differed somewhat from the ordinary connector-switch having ten levels up and ten levels horizontal. This switch had ten levels up and twenty levels horizontal, one of the latter, the tenth, being dead; in that manner you could obtain 190 sets of line terminals. Of course, I assume that Mr. Deakin would have to kill the top terminals, that is, the naught level, in order to facilitate inter-communication. I would like to ask if that kind of equipment has ever been figured on, and if it has been successful.

Gerald Deakin: It has been figured on.

A. H. Griswold: The problem of the private branch exchange service is probably as much in the lime-light today as any other telephonic problem, and practically all the telephone engineers are working along that line. Their desire seems to be to get a private branch exchange service which is intercommunicating as far as the company using the exchange is concerned, and at the same time will give proper service to the entire city or exchange. The combination can be made in a great many ways. The automatic service affords a very desirable intercommunicating device as far as the company, itself, is concerned, or as far as the service to the city is concerned. It also affords a splendid service, and to enter into a discussion of the automatic vs. the manual private branch exchange switchboard would take a long time, and at the same time, would be reviewing the subject again. So I think the thing we must work on the hardest is to get intercommunicating service and at the same time afford all of the benefits of a proper service to the entire telephone-using public.

A. H. Dyson: About the only thing I can say in connection with the paper at this time is that I believe Mr. Deakin has gone a long way towards solving one of the most important branches of the automatic telephone art. I have spent about nine years almost exclusively in the development of automatic switching devices for telephone service, and one of the most important and the hardest to solve satisfactorily has been the private exchange problem, and whether Mr. Deakin has succeeded or not, I am as yet unable to say, as I have not as yet analyzed his paper. The most serious aspect of the automatic private branch exchange is, or has been, the possibility of calls reaching the heads of the different departments when they should go to subordinates. When this happens it causes a great deal of inconvenience to business men. In other words, they are called for trivial purposes, trivial questions are asked, which occupy their time and detract from matters of more importance. I believe firmly that, whether Mr. Deakin has or has not reached the proper solution, if the automatic system prevails as the final telephone system, all service, with the exception of long-distance, I mean by that long-distance toll service, will be accomplished automatically, and further, that a connection from one city to another city, regardless of geographical separation, will be established with the assistance of only one operator. I am opposed in this view by some of the most prominent engineers, men who have given the subject a great deal of thought. The position they take is that we are tying up a system of expensive construction for an unnecessary length of time, that is, preventing the use of the toll lines between intermediate points. I believe, however, a system will eventually be developed which will so operate as to enable the establishment of telephone connections between centers geographically separated at a cost less than is now required. Long-distance connections as now established, at times, require seven or eight or more operators to extend a connection between two cities.

Mr. Deakin, I can say, from casually reading his paper, has given the matter a great deal of time and thought, and he, or his company, has gone to great expense to obtain these data, and I believe the Institute is indebted to Mr. Deakin for the information he has given us. I would like to ask the actual number of digits required to establish a connection between any points in San Francisco.

Gerald Deakin: Eight digits.

A. H. Dyson: I ask further what trouble is experienced by subscribers in calling a number of eight digits, in remembering the digits he is calling for. It has been my experience and observation that the ordinary telephone subscriber is unable to remember a number of more than four digits—I say a number of four digits, I will modify that by saying a prefix or affix of a letter or name, and four numerals. I ask if Mr. Deakin has made any observations along that line.

D. P. Fullerton: I do not know that I have much to say on the matter any more than to follow up Mr. Griswold's remarks. I agree rather strongly with Mr. Deakin's entire article. The trouble that meets us today in the telephone business is the rapidly increasing number of private branch stations, and the increasing number of them affects the service seriously in that it puts a large number of people interested, or assisting in establishing communications over which the companies have no supervision, no control. So far as automatic apparatus is concerned, I do not know whether it is the right thing to use universally or not, but I agree entirely with Mr. Deakin that the private branch exchange, whether used universally or adopted for use with a manual system, is an admirable thing. I believe it is something that telephone engineers should give considerable thought to.

Probably Mr. Deakin has solved the entire problem, and I don't believe he is very far from it, but I would advise the other telephone engineers to work on that one point and results will be appreciated by the telephone companies probably as much as any other development of the art.

R. W. Pope: I am here in this discussion not as a telephone man, but as the ultimate consumer, and the victim of the telephone subscriber who insists on seeing the head of the department or speaking with him, and refuses to give any information to the exchange operator as to his wants. This has caused me infinite trouble and I see no way of rectifying it except through the education of the general public. I have been so unfortunately situated as to be a distance of 85 ft. from the answering office of our suite in the Engineers' Building. We find that the subscribers seem to be unwilling to state their business. If they would state their business, the operator would know at once who would attend to them. But instead of that, in my case for instance, they almost always insist on speaking with the Secretary, and when they reach the Secretary, the Secretary would have to go to the office 85 ft. away or switch the subscriber on, in order to obtain such information as the present address of some one of the members. The office where the call is answered has that information right there, but as long as they will not state their business I do not believe it is possible to devise any system which will correct that evil. We must gradually educate the public as to the necessity of stating its business, when calling up, in order to be properly attended to.

A. E. Burghduff: I do not know that I can add anything to what has been said. I might give a short outline of the way our private exchange is conducted in Portland. We require a manual operator for each station. The user signals the operator if he desires a trunk or outgoing call. He then tells the operator, who makes his connection in the ordinary way, and when he is through hangs up the receiver and the operator disconnects the line. The intercommunicating line works exactly the same way. You inform the operator of the local number you desire, hang up the receiver and she calls that number and when they answer she rings you and saves your time in that way.

A point is brought up in Mr. Pope's remark that everybody wants the head of the department—not the head of the department, but the manager. With the automatic private branch exchange working entirely automatically, I see no way of preventing every one calling and getting the manager. It seems impossible to conceive of any device that will cure that, but in actual practise, with a large proportion of these people talking to the operator, she can direct them to the right department even though they ask for the manager.

W. Lee Campbell (by letter): I have read Mr. Deakin's paper with a great deal of interest and profit. I wish to take this occasion to commend him and his company for the decided success which they have attained in the installation and operation of private branch automatic switchboard equipment in San Francisco. The practise of the San Francisco company evidently has been developed to a point of high efficiency.

In connection with this paper I hope that a description of the automatic private branch exchange installed in the factory of the company making this apparatus, and connected by trunks to the public automatic exchange of approximately 30,000 stations and eight offices operated by the Illinois Tunnel Company in Chicago, Illinois, will be of interest.

This private branch exchange switchboard serves 100 individual line telephones and 12 extension telephones, and is equipped with 100 line switches, 10 first selector switches, 10 connector switches for completing local calls, three connector switches for completing incoming trunk calls, and three repeaters for outgoing trunk calls. The three incoming trunks each terminate in one of the connector switches, just mentioned, at the private branch board and in fourth selector banks at the Brooks office of the Illinois Tunnel Company. They are also equipped with repeaters at the Brooks office.

The three outgoing trunks each terminate in first selector banks at the private branch board, where they are equipped with repeaters, and terminate in regular line switches at the Brooks office.

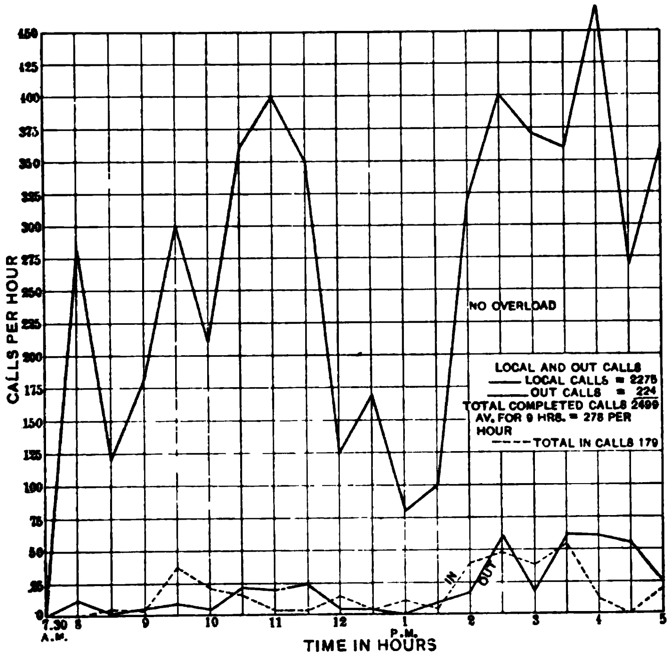
Local or intercommunicating calls in the company's factory are made by using three-figure numbers. These numbers run from 100 to 199. Outgoing calls are made by prefixing the figure 2 to any number taken from the Illinois Tunnel Company's public directory. The purpose of the prefix is, of course, to put the private branch exchange line into connection with an idle trunk line to the Brooks exchange of the Illinois Tunnel Company. After that is accomplished the call proceeds in the usual manner.

Considerably over half the private branch stations, however, are not allowed to send or receive outside calls. Each employee whose service is restricted to intercommunicating service, is automatically prevented from making outside calls by an attachment, which, whenever he calls the prefix 2, keeps him from securing a connection with the trunk, and gives the buzzing busy signal.

The numbers of officers or employees of the company who are allowed to receive incoming calls, appear in the public directory with a prefix. For example, the number of the station which is locally 170 appears in the public directory 5891–70. A subscriber to the Illinois Tunnel Company's system, when calling 5891–70, operates a first selector, second selector, third selector and a fourth selector in the public system, when calling the first four figures of the above number, that is, 5891. This puts his line in connection with an idle trunk to one of the three incoming trunk connector switches on the private branch board, so that when he calls the last two figures, that is, 70, this connector switch is operated and extends the connection to telephone No. 70.

The automatic ringing interrupter, which serves the three incoming connector switches, is arranged differently from that which serves the connector switches which handle local calls, so that when a local telephone is being rung on account of a call coming in from the outside, the party receiving the call is aware of the fact.

The circuits in connection with the three outgoing trunks, from the branch board, are so arranged that if one of the subscribers should attempt to make an outgoing call when all of the three trunks are busy, he will receive the busy signal so soon as he turns his dial from finger hole No. 2, which he does in attempting to secure a trunk.



The incoming trunks from the public exchange are arranged in the same way; that is, if any public exchange subscriber calls 5891, when all three of the incoming trunks are busy, he will receive the busy signal.

The heavy load which a small automatic switchboard of this type carries successfully, and the high efficiency of small groups of automatic switchboard trunks, mentioned by Mr. Deakin in his paper, are attested by the curves in the accompanying figure.

One of these curves shows the intercommunicating calls per hour made from the opening of the factory at 7:30 a.m. until the closing at 5:00 p.m. Another shows calls per hour received on the incoming trunks, and a third shows calls per hour sent over the outgoing trunks.

It will be noted that the total number of local calls made during the day was 2275, the total number of out calls sent was 224, making the total number of originated calls 2499.

Between the hours of 3:30 and 4:30 p.m. (the busy hour of the day) the group of 10 connectors for completing local connections handled a total of over 400 calls, without being once overloaded. Similar very high efficiencies are shown during the busy hours for the small incoming and outgoing trunk groups.

A number of busy hour local calls were timed with a stop watch, with the following results:

Time required to call	3.5 seconds
Time required for called party to answer	8.1 "
Time spent in conversation	30.1 "
Average time required for each connection Total	41.7 seconds

Lloyd D. Gilbert: Would Mr. Deakin consider an automatic installation superior to an inter-communicating system, we will say, for an industrial factory having twelve or fifteen phones, service, maintenance, and everything considered?

Gerald Deakin: With regard to the ability of the automatic private exchange to afford service equivalent in all respects to that given by the manual private exchange—early in the development of the commercial private exchange, we were fortunate enough to encounter a very large corporation, the officials of which objected very strongly to the receiving of or the making of exchange calls. As I stated in the paper, this objection was overcome by placing two bells on each line, one adapted to ring on exchange calls and the other on local calls. The officials of the corporation did not object to answering local calls, in fact they preferred to answer such calls. This system further permits the clerk or secretary of the official to establish the outgoing exchange calls.

It has been argued that the manual private exchange operator acts as an information bureau with regard to employees of the company by which she is employed, as well as an intermediary, and by so doing removes the burden of inquiries from other employees. While this condition may be true in many of the smaller systems, it does not always hold in the larger business organizations. For example, in any large concern, the operator could not be expected to know by name all employees and even if she did, she would probably not know the local telephone number of each. The result is, in actual practise, that many calls are thrown by the operator to the head of some department. The burden of locating the proper party and directing such a call to the proper number in case the call has to be changed, is then placed upon the called but not wanted party. Furthermore, the officials in a large corporation can rarely be obtained directly. Calls for them are nearly always intercepted by their clerk or secretary. In such cases as these the calling party is put to the annoyance of dealing with both an operator and clerk before he can obtain the party wanted. I am merely citing these points to illustrate the fact that the objections which have been raised against the automatic system are also applicable, to a considerable extent, to the present manual system. In an automatic system the extensive listing of numbers in the telephone directory permits a large percentage of the total in calls to be made direct to the proper station. Those calls which, for one reason or another, cannot be made direct, can be made through the receiving cabinet.

Mr. Dyson made the statement, I believe, that toll connections could be more readily established automatically than manually. I agree with Mr. Dyson in this matter. We have done this on a small scale between San Francisco and Oakland and I can see no reason why the system should not be extended to long-haul business, if adequate provision is made for the customary handling of service in case of trouble on the line.

Mr. Dyson has questioned the ability of the subscribers to call, with any degree of accuracy, eight digits, which, with the development of the automatic private exchange into a hundred thousand line system, is sometimes necessary. This is true to a certain extent. If the eight digits represented the number of some single unit, it would be difficult to remember the number while calling. The eight digits, however, represent a composite number of three parts and for this reason somewhat less difficult to remember. For example, consider a call from one private exchange station to another. The first digit called would be 0; this is to establish the trunk connection, and is not difficult to remember. The next five digits would represent the number of the called exchange as a whole. The remaining two digits would represent the number of the proper local in that exchange. There is no question but that the remembering of numbers is an important point in any system, and one which cannot be overlooked when an attempt is made to eliminate irregularities in operation, and it is well known that many wrong numbers are given by subscribers who attempt to call by memory, even when the numbers are short. The addition of a small writing pad to each telephone, upon which the number to be called may be written, would, I believe, be of value in many cases. The calling of wrong locals in an automatic private exchange, apart from disturbing the called party, does not place any great burden upon the calling party. The system as now arranged permits a second local to be called when the party first called hangs up. The calling party is not required to disconnect.

A valuable feature of the automatic switchboard, which, I believe, has not yet been brought out, is its ability to establish, simultaneously, as many connections as its facilities will accommodate. In watching the operation of one of the larger switchboards, I noticed at one time, four mechanical operators start at almost identically the same time. There could not have been a difference of more than a second between the starting times of all four switches. In a corresponding, but manually operated system, at least eight or ten seconds would have to have been devoted to each call, with the result that all except the first station would be subjected to a delay.

Mr. Pope made the remark that most people do not know whom to call when information is wanted and a private exchange is involved in the connection. This, I believe, is largely due to the fact that the present method of directory listing does not give any information as to the different departments maintained by a company. Mr. Pope stated that a great many calls are received by him which should have been directed to someone else. Had the particular department with which connection was desired been listed in the directory, I have no doubt Mr. Pope would have been saved the annoyance of answering many misdirected calls.

The successful operation of an automatic switchboard depends to some extent upon its location. For use in the larger cities, it is safe to figure upon boards of all sizes from 10 stations up. Very small exchanges can be economically handled when two or more of them are in the same building, which permits the use of a common switchboard.

Arthur Bessey Smith: (communicated after adjournment): Mr. Deakin's paper is full of interesting and valuable matter, which will bear an extended and careful study. I wish especially to call attention to one feature of private branch exchange operation to which he has given some attention. It is the matter of indirect calling, which has been the cause of considerable annoyance to telephone users.

The subscriber who is otherwise obliged to work his way through the offices of two or three, or perhaps four, operators, cannot be censured for desiring to throw the responsibility and labor of his work on to someone else, and naturally the private branch exchange operator in his own building is the one selected. The busy man feels the interruption to his work. However, when he is able, by the mere turning of a dial, to place his call directly, the interruption is far less than to send it indirectly through the private branch exchange operator. The evil of the indirect call is sufficiently great to have received the attention of the general public. Sometime ago the writer saw, in a paper devoted to humorous articles, the proposal to organize a mutual protective league of telephone subscribers for the purpose of eliminating this evil by refusing to answer the telephone unless the calling party were actually present on the line.

Now the writer does not seriously advocate any such system as this, but we feel that the dictates of common courtesy should lead the telephone user, especially one who uses the automatic system, to make his calls directly, so as to be present on the line when the desired party answers. Since to call on the automatic is relatively so easy, the automatic system should at least be given the credit of being a force which makes for politeness and mutual regard.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 17, 1912.

THE APPLICATION OF AUTOMATIC SELECTING DEVICES TO TELEPHONE MULTIPLE SWITCHBOARDS

BY ALFRED H. DYSON

This paper will discuss means and certain results obtained by the application of selective switches to common battery multiple telephone switchboard systems.

The manual common battery multiple telephone switchboard system has now been in commercial use in practically all of the larger cities for more than a decade. As at present used its arrangement has reached the limit of development and is structurally the least complex of all telephone systems adapted to provide service for a large number of subscribers, but when applied to the larger sized exchanges it is found to be very expensive in first cost and also is believed to be unnecessarily expensive in operation. Its first cost increases in an increased ratio with the increased number of lines. This is also true of its operation, for the reason that with the increase in number of subscribers' lines the number of calls per line per day also increases, with the result that the ratio between the number of lines and the number of operators for effecting the connection of such lines is decreased, that is, the percentage of operators to lines is increased.

Briefly, the arrangement of the manual multiple switchboard system, as now in use, is such that each subscriber's line terminates on the switchboard in an answering jack with which is associated a signal lamp and multiple jacks, there being as many multiple jack terminals of each line as there are sections of switchboard—each section consisting of three operators' positions. For the interconnection of a line as a calling line with a line as a called line there are provided what are termed connecting cord circuits, each provided with a pair of plug terminals known as answering and calling plugs, and a pair of signal lamps termed answering and calling supervisory lamps. Each cord circuit is in addition provided with keys which enable the operators to connect in circuit their telephone apparatus and to establish circuit for the ringing current for actuating the signal bells of the substations. There are placed before each operator answering jack terminals of as many lines as an operator is capable of establishing connections for and as many connecting cord circuits—usually about fifteen—as are required to establish such connections at the busiest moment.

If it be a "multi"-office exchange, there are provided multiple jack terminals of trunk lines which lead from each office to each of the other offices of the exchange, there being a multiple jack terminal of each trunk within the reach of each subscriber's operator. In addition there are provided in each office as many incoming trunk circuits as may be required to handle the connections trunked into a particular office from the other offices. These circuits are each provided with two signal lamps termed calling supervisory and disconnect lamps, and keys for establishing circuit for current for actuating the signal bells of the called substations. These incoming trunk circuits usually terminate in connecting plugs before special operators, usually called incoming trunk or B operators, as distinguished from the subscribers' operators, who are sometimes called A operators. There are as many incoming trunk circuits placed before each such operator as may be handled by an operator during the busiest moment, *i.e.*, during the moment of the greatest number of coexisting trunk connections. Usually an operator is provided with about 30 such circuits. There is also provided before the incoming trunk operators a multiple jack terminal for each line of the office, there being one such terminal for every three or less operators.

The operation of the multiple switchboard system is such that upon the removal of the receiver from the switchhook by a calling subscriber the line signal lamp of the line of such subscriber is automatically illuminated. The operator before whom said lamp is located, upon observing that it is lighted, inserts the answering plug of an idle cord circuit into connection with the answering jack of the line of the subscriber, and by the actuation of a key associated with the cord circuit it is connected telephonically with the calling subscriber. The operator thus ascertains the number of the called subscriber. If it be a single office exchange, the operator, by touching the sleeve terminal of the multiple jack of the line of the wanted subscriber with the tip of the associated calling plug of the cord circuit, ascertains the busy or idle condition of the line. If the line be busy the calling subscriber is notified that connection cannot be established. If the line be idle she then inserts said calling plug into connection with the said multiple jack terminal and actuates a key associated with the cord circuit, which results in the transmission of current over the called line to actuate the substation signal bells. The projection of the ringing current thereafter continues periodically until the removal of the receiver from the switchhook of the called substation, at which time the ringing current is permanently disconnected from the line and the calling and called subscribers automatically placed in telephonic connection. Whenever the plugs of a cord circuit are in connection with a line and the receivers off the switchhooks the supervisory lamps are in their normal or unlighted condition, but upon replacing the receiver upon the switchhook at the calling substation the answering supervisory lamp is illuminated, and upon replacing the receiver upon the switchhook at the called substation the calling supervisory lamp is illuminated. The principal object of these lamps is to inform the operator when disconnection is desired, *i.e.*, when the plugs of a cord circuit should be disconnected from the jack terminals of the lines. This is done when the two connected subscribers replace their receivers upon their switchhooks after completion of conversation. These lamps are also used for the purpose of signaling the operator after a connection has been established if her assistance is desired.

If it be a "multi"-office exchange and a calling subscriber desires connection with a subscriber whose line terminates in some office other than the office in which the line of the calling subscriber terminates, then the operator would communicate—by means of a call circuit—with an incoming trunk operator, in the office in which the called line terminates, giving to the incoming trunk operator the number of the line of the called subscriber. The incoming trunk operator, upon ascertaining the number of the called subscriber, assigns a trunk to be used. Upon assignment of such trunk the subscriber's operator inserts the calling plug associated, with the answering plug inserted in the answering jack, into connection with a multiple jack terminal of the trunk assigned. The incoming trunk operator, upon ascertaining the number of the called subscriber, by touching the sleeve of the multiple jack terminal of the line of the called subscriber with the tip of the plug of the trunk circuit assigned, ascertains the busy or idle condition of the called line. If such line be busy the calling subscriber is notified by means of a suitable signal. If the called line be not busy the incoming trunk operator inserts the plug of the assigned trunk into connection with the multiple jack terminal of the called subscriber, and actuates a key associated with the assigned trunk, which results in the projection of current over the line to actuate the signal bells of the called substation. This ringing current continues periodically until the removal of the receiver at the called substation, or until the removal of the trunk plug from connection with the multiple jack of the line called. Upon removal of the receiver from the switchhook at the called substation the ringing current is permanently disconnected from the line and the two subscribers automatically placed in telephonic connection. The signal lamps associated with each incoming trunk circuit indicate to the incoming trunk operator when disconnection should be effected, which is accomplished by simply removing the trunk plug from connection with the multiple jack terminal of the line.

The introduction commercially of the automatic telephone system has resulted in the production of a modified form of multiple switchboard system. This system I shall herein term the " automatic call distributing system." This system materially reduces the cost of operation and also, in the larger central offices, reduces the first cost of the central office equipment.

The arrangement of the automatic call distributing system differs from that of the manual system in that the answering jacks, their associated line lamps and the answering cords of the cord circuits are eliminated. In lieu thereof automatic selector switches are provided, which, upon the removal of the receiver from the switchhook at a calling substation, ***automatically connect a calling line with the first idle connecting cord circuit*** to which the calling line has access. In other words the calls are automatically distributed before the operators. There are a number of arrangements of switches for accomplishing this result.

By one arrangement a small ten-point switch is provided for each line and a sufficient number of 100-point switches to accommodate the maximum number of coexisting connections. This arrangement acts in such a way that upon the removal of the receiver from the switchhook at a calling substation the ten-point switch associated with the line is automatically rotated to select an idle one of ten 100-point switches which, upon selection, is automatically actuated to select and connect with an idle one of 100 connecting cord circuits. Upon the completion of the second selection a signal lamp associated with the selected cord circuit is automatically illuminated, indicating to the operator, before whom such selected cord circuit is located, that a connection is desired.

Another arrangement is to provide a 100-point switch for each connecting cord circuit and a number of 100-point line selector switches equal to the number of the maximum coexisting connections at the busiest moment of the day. The operation of this arrangement is such that upon the removal of the receiver from the switchhook, a switch associated with an idle cord is automatically actuated and selects an idle line selector, which said line selector is adapted upon its selection to automatically select a multiple terminal of the calling line. When this selection has been made a lamp signal associated with the selected cord circuit is displayed before the operator, indicating that a connection is desired.

Another arrangement, and the one preferred by the writer, is to divide the lines as calling lines into groups of 100 lines each and to provide for each group of 100 lines as many 100-point line selector switches as there will be coexisting calls in the associated group of 100 lines during the busiest moment of the day. To each line selector switch is electrically connected a 100-point cord selector switch. The operation under this arrangement is such that upon the removal of the receiver from the switchhook by a calling subscriber, an idle one of the line selectors and its associated cord selector are actuated. The line selector automatically selects and connects with a multiple terminal of the calling line, and the cord selector automatically selects and connects with a multiple terminal of an idle cord circuit. Upon such selection of the line and cord, a signal lamp associated with the selected cord is illuminated, indicating to the operator before whom the cord and lamp are located that a connection is desired. The operator observing the lighted condition of the lamp, after actuation of a key associated with the said cord circuit, ascertains the number of the wanted substation. Thereafter—if it be a single-office exchange—the operator, by touching the sleeve of a multiple jack terminal of the line of the wanted subscriber with the tip of the connecting plug of the selected cord circuit, ascertains the busy or idle condition of such line. If the line be busy she notifies the calling subscriber that connection cannot be completed. If the line be idle she inserts the connecting plug into connection with the multiple jack and actuates a key associated with the cord circuit, which projects over the called line current which actuates the signal bells of the substation of the called subscriber. This signaling current is maintained periodically until the removal of the receiver from the switchhook at the called substation. Upon such removal the signaling current is automatically disconnected and the two subscribers placed in telephonic connection. Associated with the connecting end of each cord circuit is a signal lamp termed a supervisory lamp, which indicates to the operator when the called subscriber removes the receiver from the switchhook and also when the receiver is replaced. The call signal lamp associated with the answering end of the cord circuit acts also as a supervisory lamp which indicates, after connection with the called line, when the receiver at the calling substation is off or on the hook. After completing conversation the two subscribers, by replacing the receivers upon their respective switchhooks, cause the illumination of the two supervisory signal lamps, which indicates to the operator that disconnection is desired, which she accomplishes by removing the connecting plug from connection with the multiple jack terminal of the line of the called substation.

If it be a multi-office exchange and if a calling subscriber desires connection with a line terminating in some other office, then the connection is trunked to the distant office and established as described in connection with the manual system.

In order to arrive at the difference in the number of operators required and the difference in first cost between the two systems, it is necessary to know:

1. The number of calls per line per day.
2. The number of calls originating during the busiest hour.
3. The number of connections an operator can establish in a single office exchange during the busiest hour.
4. The number of connections an operator can establish in a multi-office exchange during the busiest hour.

Upon the number of calls per line per day and the number of calls an operator can establish during the busiest hour, will depend the number of lines which may be assigned as calling lines to each operator. On the number of lines assigned to each operator will depend the number of operators' positions required to handle the traffic during the busiest hour. It is also necessary to provide connecting apparatus to accommodate the maximum number of coexisting calls at the busiest moment.

For the purpose of this discussion I shall only consider flat rate service, including individual lines and a fair development of selective party lines.

In order to determine the number of calls per line per day in exchanges of various sizes and the number of connections an operator can establish in both a single-office exchange and a "multi"-office exchange during the busiest hour, I have had reference to "peg counts" of various exchanges approximating the sizes to be discussed.

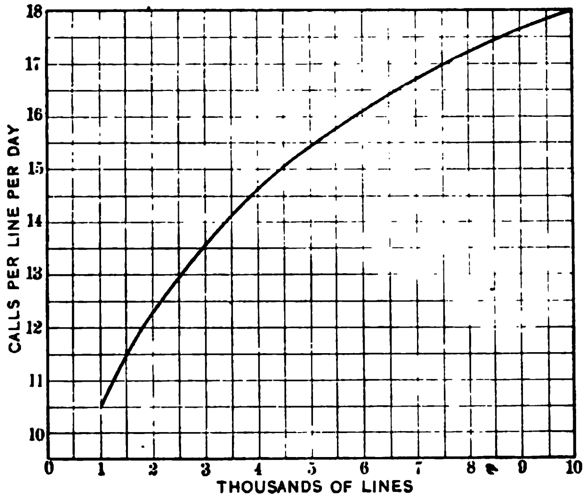


Fig. 1

Calls per line per day in exchanges varying from 1,000 to 10,000 lines. Flat rate service.

The curve of Fig. 1 illustrates the average number of calls per line per day in exchanges varying from 1000 to 10,000 flat rate lines. I do not claim this curve to be exact for any particular exchange, as local conditions are usually such as to cause a divergence, but it is a fair approximate average.

Curve *A* of Fig. 2 illustrates the average number of connections which operators in single-office exchanges varying from 1000 to 10,000 lines can establish during the busiest hour. It will be seen upon inspection that the number increases with the number of lines of the exchange. This is attributed to the fact

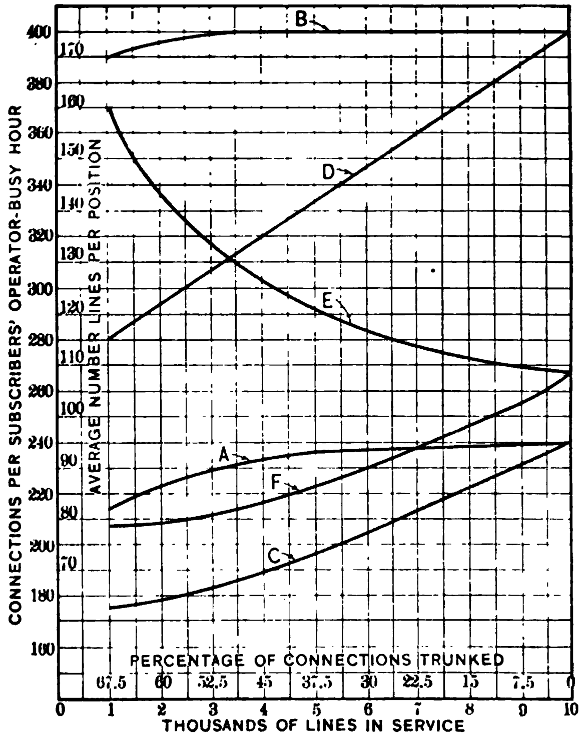


FIG. 2

Curve A shows average number connections (busy hour) per operator, in a single-office manual exchange of from 1,000 to 10,000 lines.

Curve B shows average number connections (busy hour) per operator, in a single-office automatic call distributing exchange of from 1,000 to 10,000 lines.

Curve C shows average number connections (busy hour) per operator, in a multi-office manual exchange of 10,000 lines (18 calls per line per day) when certain percentages of calls are trunked.

Curve D shows average number connections (busy hour) per operator, in a multi-office automatic call distributing exchange of 10,000 lines (18 calls per line per day) when certain percentages of calls are trunked.

Curve E shows average number lines per operator's position in a single-office manual exchange of from 1,000 to 10,000 lines.

Curve F shows average number lines per operator's position in a multi-office manual exchange of 10,000 lines (18 calls per line per day) when certain percentages of calls are trunked.

that in the smaller exchanges the operators are less efficient and that the fewer the number of calls per line per day the less the regularity with which the calls originate, which results in a greater number of idle periods.

From curve *A* of Fig. 2 has been plotted the curve *E* of Fig. 2 which illustrates in single-office exchanges varying from 1000 to 10,000 lines the number of lines per operator's position, when the number of calls per line per day varies from 10½ in 1000-line offices to 18 in 10,000-line offices. It may be observed that although in the larger exchanges an operator can establish a greater number of connections per hour, nevertheless the number of lines allotted as calling lines to each operator is decreased, owing to the fact that the number of calls per line per day is increased.

Curve *C*, Fig. 2, sets forth the average number of connections an operator can establish in multi-office exchanges of 10,000 lines, at 18 calls per line per day—when various percentages of calls are trunked—during the busiest hour.

The percentage of calls trunked from any office has been arrived at by application of the formula

$$\text{trunking per cent} = 100\,\frac{A - B}{A}\,0.75,$$

wherein *A* is the total number of lines in the exchange, *B* the number of lines in the office under consideration, and 0.75 is a factor which allows under ordinary conditions for the community of interest between the subscribers of the office. It is obvious, under the conditions assumed, that the greater the percentage of calls trunked, the fewer calls an operator can establish during the busy hour.

From curve *C* of Fig. 2 has been plotted curve *F* of Fig. 2, which sets forth the average number of lines which may be assigned to each operator in a multi-office system operated under the conditions of curve *C*, Fig. 2.

As there is not in commercial use an exchange operating under the automatic call distributing system, I have of course been unable to ascertain the actual number of calls an operator could establish during the busiest hour, but have assumed that there will be required in a single-office exchange, according to the curve of Fig. 1, nine seconds for the establishment of each connection, from which assumption I have plotted curve *B*, which shows the average number of connections an operator can establish during the busy hour, by means of the automatic call distributing system.

Allowing seven seconds additional for each connection trunked, *i.e.*, 16 seconds for each trunked connection, I have shown by curve *D*, Fig. 2, the average number of connections an operator can establish in a 10,000-line multi-office exchange, in the busy hour, in offices varying from 1000 to 9000 lines, when certain percentages of calls, as shown, are trunked. As mentioned in reference to curve *B*, this is estimated, owing to the fact it is impossible to obtain the information from actually working commercial exchanges.

The vast difference in the number of connections per operator per hour between the two systems appears abnormal, but it is believed a little thought will convince the reader that the conclusions are correct and will be borne out in commercial practise.

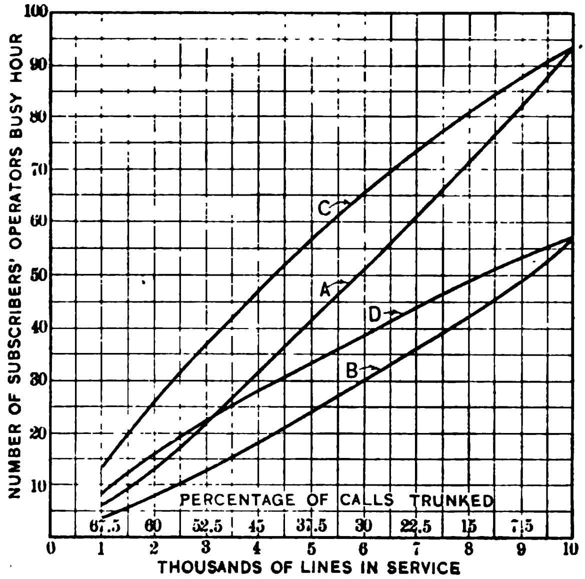


FIG. 3

Number subscribers' operators required during busy hour, as per Figs. 1 and 2.

Curve A represents single-office manual system, 1,000 to 10,000 lines.

Curve B represents single-office automatic call distributing system, 1,000 to 10,000 lines.

Curve C represents multi-office 10,000-line exchange, manual system, 18 calls per line per day.

Curve D represents multi-office 10,000-line exchange, automatic call distributing system, 18 calls per line per day.

Having arrived at the difference in number of calls per operator per hour, in each of the systems, it is next in order to consider the difference in the number of operators required to handle the traffic of the exchanges during the period of the peak of the load, *i.e.*, during the busiest hour. In order that this may be readily ascertained I have plotted the curves of Fig. 3, in which curve

A is based upon the results of the curve of Fig. 1 and curve *A* of Fig. 2 and shows the number of operators required to handle the traffic of a single-office manual multiple switchboard system during the busiest hour. Likewise curve *B* of Fig. 3 is based upon the results of the curve of Fig. 1 and the curve *B* of Fig. 2 and shows the number of operators required to handle the traffic of a single-office automatic call distributing system exchange during the busiest hour.

Curve *C*, Fig. 3, is plotted from curve *C* of Fig. 2 and shows the number of operators required, in a multi-office manual multiple switchboard exchange of 10,000 lines, at 18 calls per line per day, to handle the traffic of an office of a particular number of lines during the busiest hour when the percentages of connections, as shown, are trunked.

Curve *D* of Fig. 3 has been plotted from curve *D* of Fig. 2 and shows the number of operators required in a multi-office automatic call distributing exchange of 10,000 lines, 18 calls per line per day, to handle the traffic of an office of a particular number of lines when the percentages of connections as shown are trunked. The difference in number of operators in the two systems will, by inspection of the curves of Fig. 3, be apparent. As stated, the curves of Fig. 3 set forth the number of operators required during the busiest hour. It will, however, be understood by all traffic men that the number of operators required at all other hours of the day may be accordingly reduced.

Having ascertained the number of operators required for the operation of an exchange of given size, both single and multi-office, the annual saving in operators' wages and other costs incidental thereto may be readily ascertained. The saving is found to be at first glance almost inconceivable, but it is believed by the writer that the ratio will be approximately borne out in commercial practise.

While the automatic call distributing system has been well developed by at least one interest and it is understood also by others, the possible variations in the methods by which the result may be accomplished, three of which have been herein described, leave wide room for variation in the first cost of equipment for producing in exchanges of various sizes the operating results which I have set forth. It may be said that each of the outlined ways of accomplishing the results of automatic call distribution will maintain the advantages indicated by the curves.

In view of the possible wide differences in amount of equipment, depending upon the particular system preferred, and also for other reasons which a little thought will make apparent, it will be understood that the difference in relative percentage of first cost of manual systems and the automatic call distributing system will vary. The question of cost has, however, been given careful attention by the writer and figured out for a particular system. As a result I have plotted the curves of Fig. 4, which

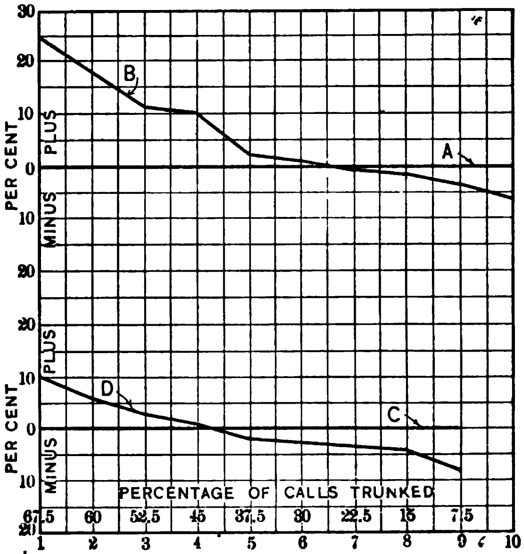


FIG. 4

Curves A and B represent percentage differences in cost of a single-office exchange of from 1000 to 10,000 lines. Curve A represents manual and curve B represents automatic call distribution.

Curves C and D represent percentage differences in cost of a multi-office 10,000-line exchange (18 calls per line per day) when certain percentages of calls are trunked. Curve C represents manual and curve D represents automatic call distribution.

are intended to show difference in percentages of first cost of all central office equipment with the exception of long distance equipment.

The curves *B* and *D* of Fig. 4 are not based on apparatus built for commercial use, but are estimated on what, in the opinion of the writer, the apparatus will cost installed.

Curves *A* and *B* of Fig. 4, wherein curve *A* represents manual and curve *B* automatic call distributing, are intended to show the percentage difference in first cost of the central office equipment, exclusive of long distance equipment, of single-office exchanges varying from 1000 to 10,000 lines, when the number of calls per line per day varies according to the curve of Fig. 1.

The curves *C* and *D* of Fig. 4, wherein curve *C* represents manual and curve *D* automatic call distributing, are intended to show, in multi-office exchanges of 10,000 lines, the percentage difference between the two systems in first cost of the central office equipment, except long distance equipment, of offices of the particular number of lines as shown, when the number of calls per line per day is 18, and when the percentages of connections, as shown, are trunked.

An inspection of the curves will show the first cost in single-office exchanges of the central office equipment of an automatic call distributing exchange of 6750 lines or less to be greater than that of a manual exchange of equal number of lines, while for single-office exchanges of a greater number of lines the first cost of the automatic call distributing becomes less than that of a manual exchange of like number of lines.

In multi-office 10,000-line exchanges operating under conditions hereinbefore set forth, the first cost of the central office equipment of the automatic call distributing system is less than that of the manual system, when the size of an office exceeds about 4300 lines.

Thus from the above we find, under the conditions herein assumed, that the cost of operation of the automatic call distributing system is, for all sizes of exchanges, ***less than that of the manual multiple telephone switchboard system***, and that for the larger sized offices, *i.e.*, offices of the greater number of subscribers' lines, not only the cost of operation, but also the first cost, of the automatic call distributing system is less than that of the manual system.

In considering cost of operation I have not so far taken into consideration the relative cost of maintenance. As the switches for accomplishing automatic call distribution are more complex than the central office apparatus used in the manual system, the cost of the maintenance of these switches will somewhat increase, in the writer's opinion, the total annual maintenance cost of the central office apparatus. But it must be understood that the amount of the apparatus which would be used in the manual system is decreased, when automatic call distribution is applied, the result being that the increased annual maintenance cost of the automatic call distributing system, owing to the selective switches, over that of the manual system, will be very slight; it may in fact be considered negligible, when compared with the great saving in operators' expense.

What I have hereinbefore stated has had reference particularly to new installations of central office equipment. Before concluding the discussion I will state that automatic call distribution may with economy be applied to existing exchanges. As an example, considering a single-office exchange of say 6000 lines, it is found by reference to curve *A*, Fig. 3, that without automatic distribution approximately 51 operators are, during the busiest hour, required to handle the traffic, while with automatic call distribution with the same number of operators, (see curve *B* of Fig. 3) the traffic of approximately 9300 lines may be handled during the busy hour. Thus by installation of the automatic call distribution apparatus and the necessary multiple jack terminals for the number of lines over and above 6000 lines, the number of lines of the exchange may be increased approximately 55 per cent. Thus with only the number of operators necessary to handle the traffic of the original 6000-line manual exchange, the traffic of an exchange of 9300 lines may be handled. The cost of additional equipment necessary to accomplish this result, it is believed, would not be greater than the cost of the equipment necessary to increase a manual exchange from 6000 to 9300.

Or, if it is not desired to increase the number of lines of the exchange, the cost of operation may be reduced by the installation of the apparatus necessary for automatic call distribution, and it is believed that the decrease in cost of operation will be much greater than the interest on the additional investment and the additional cost of maintenance of the automatic call distribution apparatus.

Another manner in which automatic call distribution may be applied to existing exchanges is to install equipment necessary to handle the traffic during the busiest hour with automatic call distribution apparatus and thereafter, by dividing the switchboard including the multiple equipment, utilize the positions not then required, as a separate switchboard, which may then be equipped with the automatic call distribution apparatus and by installation of trunking apparatus and circuits, the exchange may be converted into a multi-office of a greater number of lines. The increase in number of lines will depend upon the number of operators' positions of the original equipment saved by the change.

Either of the above changes from the manual system to the automatic call distribution system can be accomplished without impairing in any manner the efficiency of service, as the change may be made on each position of the switchboard and on each line without disturbing in any manner the other positions or lines of the office.

None of the above could be accomplished if it should be attempted to change from the manual multiple switchboard system to any other system other than the automatic call distribution system.

Should the attempt be made to change an existing manual exchange to an automatic exchange, not only would the numbers of the substations of all the lines have to be changed, requiring a new directory and confusion on the part of subscribers, but all of the telephones would have to be changed or replaced and an entire new switchboard provided, incurring enormous expense in addition to confusion and probable dissatisfaction in service.

Should the attempt be made to change an exchange from a manual multiple switchboard system to the so-called "automanual" system, the same confusion in reference to change in numbers on the part of the subscribers would be present, and in addition it would mean the installation of a new switchboard equipment of apparatus of greater amount and complexity than would be required even in a full automatic system.

A telephone company has but two objects—to give satisfactory service to its subscribers and a reasonable return to its stockholders on the capital invested.

In accordance with all that has been said, it is firmly believed by the writer at this time, that—excepting possibly the largest exchanges—when all items of expense are considered, and especially in reference to existing manual exchanges, the automatic call distribution, as herein explained, will be found to be more economical and satisfactory than any other known telephone system adapted to give satisfactory service to its subscribers.

DISCUSSION ON "THE APPLICATION OF AUTOMATIC SELECTING DEVICES TO TELEPHONE MULTIPLE SWITCHBOARDS" (DYSON), PORTLAND, ORE., APRIL 17, 1912.

A. H. Griswold: I would like to ask Mr. Dyson if it is the plan to distribute a call to the first idle operator, or the first idle cord.

A. H. Dyson: It may be the first idle operator, or you may arrange it so that the calls for a particular operator will be distributed between thousands of lines, or hundreds of lines.

Gerald Deakin: I want to assume this: suppose two calls are coming in almost simultaneously, the first call would reach the first cord, the second call may go to the second, or the first idle cord, and further on there may be other idle operators who would really give much quicker attention to the call. Is there the possibility of several calls coming in almost at the same moment being loaded up before one operator?

A. H. Dyson: The system is capable of being arranged either way; also it may be so arranged that a call will appear before an operator only when she is idle, but I don't think that is a good arrangement, because it enables the operators to loaf on their jobs. I believe that the loading of an operator will only occur at the beginning of business. After that, calls will appear before the operators in rotation and will be taken down in rotation. An operator is placed in connection with the calling subscriber if she is not already busy, in approximately one-half a second after removing the receiver from the hook.

H. M. Friendly: Mr. Dyson's paper deals with certain apparatus to reduce the number of answering jacks. I ask if he has ever considered reducing the number of multiple jacks by the use of such equipment?

In private branch exchange work that requires that two or more trunk equipments be provided at the central office, it is often necessary for the operator to test successively all of the trunks of a particular private branch exchange, or exchange subscriber, before she finds a disengaged trunk, or finds that there are no disengaged trunks. This requires time, and the consequent clicking due to such tests is more or less annoying to the calling subscriber who may be holding the line in waiting for the called party. The greater the number of trunks, and the more busy the private branch exchange, the more serious this trouble becomes. This is aside from the fact that a great many multiple jacks, each appearing at every section, are required for this service. It has occurred to me that by installing a sub-multiple, and that multiple appearing at only one, or say at the most, three sections, and then associating these various sets of multiple or individual jacks with automatic trunk selectors that have access to all the trunks of the private exchange, the operator would be relieved of all testing, and the delays and annoyances incident to it. She would simply plug into either of her several individual jacks without testing, or if jointly used by several sections in multiple, test relatively few jacks before finding a disengaged one. The selector equipment could obviously be arranged to signal directly by auditory means to the calling subscriber, or by visual means to the operator, if all the trunks are busy. I would be interested in knowing if any such scheme has been contemplated.

A. H. Dyson: I will answer by saying that each private branch exchange trunk may be equipped with a selector switch. And the private branch exchange jacks, instead of being multipled through the various sections of the board, may be individual to each section and connected to the bank contacts of the switches, the operation being such that an operator on receiving a call for a private branch exchange plugs into any one of the jacks on her section assigned to the particular private branch exchange wanted, which act causes the switch of an idle trunk line to select the jack plugged into by the operator.

This arrangement saves a certain percentage of jacks required on each section and also obviates the necessity of testing the private branch exchange jacks until an idle trunk is found.

Gerald Deakin: Would that not require a separate jack in each section rather than a jack multipled through all sections?

A. H. Dyson: Yes, at the present time you have a number of jacks to each section equal to the number of trunks leading to a private branch exchange, and instead of connecting these jacks in multiple you make them individual contacts with the switches associated with the trunk and multiple the jacks on the switches.

Gerald Deakin: That would not be very economical in the larger exchanges; for example, you would have 30 switches or contacts for each trunk in an exchange of thirty sections.

A. H. Dyson: Take two switches on two trunks connected 100 sections. You would employ two 100-board switches and you would use about the same number of multiple jacks you now have.

A. E. Burghduff: I ask if your system contemplates the use of an individual selector for each subscriber's line.

A. H. Dyson: As stated in my paper, there is one arrangement by which it may be accomplished. The arrangement is to provide a series of switches common to a group of lines, say a hundred of them. We have ten 100-point switches taking off a hundred lines, and then upon the removal of the receiver, an idle one will be located to select the line better.

By having ten you could have ten full system connections as calling lines for each group; they can be continued to any extent you desire.

Arthur Bessey Smith (by letter): The method which Mr. Dyson has described, for handling telephone traffic, has been productive of considerable thought by a number of telephone engineers, in the past few years. Various names have been applied to it, such as the following: "automatic traffic distributor," "automatic call distributing system," and even "semi-automatic," although the last term should not be encouraged. In general, the writer concurs with the conclusion reached by Mr. Dyson, but feels that several points might profitably be more fully expanded.

The manual telephone switchboard operator works at her greatest efficiency during the busy hour, when the calls are coming in at their maximum rate for the day. As the load on the board falls off, each operator has less to do. Consequently, telephone companies attempt to maintain the efficiency of their operators by reducing the number at times of light load. Though obviously cheaper than maintaining the full force all day, it leaves much to be desired.

When an operator has to handle more than one position, she cannot answer calls as fast, since she must reach farther and with more effort on each connection. The reduction of efficiency is clearly shown by the curve in Fig. 1. Starting with a standard of 100 per cent as the load which she can handle at one position, she can care for only 73 per cent as many calls when two positions are assigned. For night work, when one operator must tend many positions, the efficiency is very low. Ten positions give us a load only 18 per cent of her full one-position ability. Thus the expedient of adjusting the number of operators to the load results in great loss of efficiency without making the work any easier.

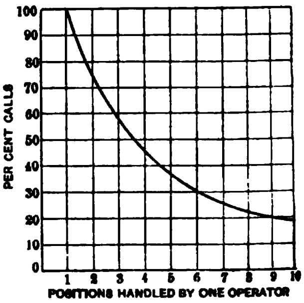


Fig. 1

If the load curves of each of the positions on a board be examined it will be found that the busy periods do not occur at exactly the same time on all positions. This causes a further loss in efficiency. Fig. 2 was taken from an actual peg count and illustrates the inequality very well. From 6 to 7 a.m., position 9 is the only one to have an appreciable load. From 10 to 11 a.m., positions 4, 6 and 9 have an increased load, while 5, 7, 8 and 10 have very much less to do. The afternoon peak comes between 4 and 5 on positions 5 and 9, between 5 and 6 on positions 7 and 10, while it is as late as between 7 and 8 on positions 4, 6 and 8.

In general, the traffic manager aims to equalize the load by rearranging the lines at the immediate distributing frame so that as far as possible the busy time will be equalized. This is a matter of difficulty, for it requires constant attention and much thought and labor. Very few exchanges are successful in securing it.

There is another great loss of efficiency due to the evil of "rushes." For instance, when we say that 225 calls were handled by one operator in one hour we have only a partial idea of her speed. During that hour the calls did not come in an even, steady stream. There were periods of rush, when she may have been answering calls at the rate of 700 or 800 per hour, followed by short periods of slow calling or even idleness. The observations of experienced operating companies has shown that even during the busy hour, an operator is actually working only 50 per cent to 67 per cent of the time, the latter figure being unusual.

Formerly the only known method of reducing the inequality was "team work." Each operator is trained to keep lookout over the position to her right and left so that if her neighbor has more than she can do, assistance can be given. Though this reduces the evil a little, it still fails to get at the root of the matter.

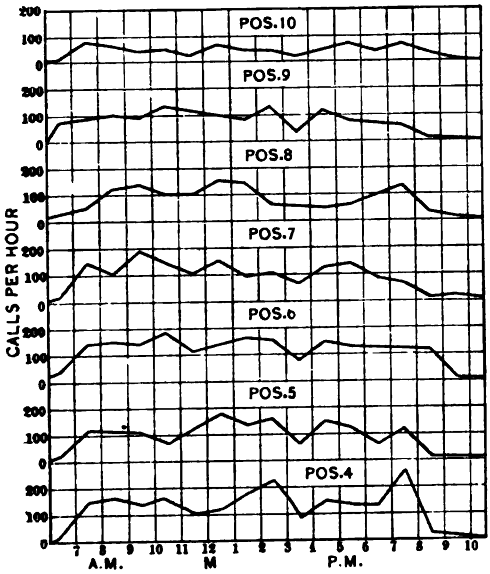


FIG. 2

The ideal condition in manual operation would be reached if there could be secured an absolute uniformity of load on all the operators. We could then reduce or increase the number of positions to suit the load, each working at full efficiency all the time. The momentary rush would lose its terror, being lost in the general average. Since one position is as busy as another, one has no necessity for helping another. The elimination of the answering cord reduces her manipulations very materially. On a conservative basis it is believed that this will save about 22 per cent of the time required per call.

In addition to the 22 per cent saving in time secured by simpler operation, we have a large saving in the uniformity with which calls come to each operator. Under good operating conditions at ordinary manual boards, the operator is actually engaged only two-thirds of the busy hour. By means of the call distributor this can be raised to five-sixths, or at a loss of only ten minutes in the hour. This alone amounts to a 25 per cent increase in efficiency. The saving of 22 per cent in time per call means a gain of 28.5 per cent in efficiency, which taken in connection with the 25 per cent makes a total increase in efficiency due to these two causes of 60.6 per cent. This takes into account only the busy hour load.

Adjustment of Operating Force to the Work. It has been found in ordinary practise that the average number of calls answered by an operator is about 75 per cent of what she answers during the busy hour. This is known to be due to the loss of speed incurred by having one operator tend two or more positions. With the traffic distributor no operator ever has to tend more than one position, because as the force is reduced, the vacant positions are made busy, thus restricting the traffic to the occupied positions. Thus each girl may be held up to her busy hour load, so that no loss need occur from this source. This will add about 33⅓ per cent to the operator's average all-day efficiency. The number of positions occupied can be in direct proportion to the total traffic.

Saving in Operators' Salaries. Since the operators' speed has been increased it will take fewer operator-hours to run the board. The increase of 60 per cent in busy hour efficiency mentioned above means a saving of 37.5 per cent in force, or a busy-hour force only 62.5 per cent as large as under ordinary conditions.

The increase of speed of 33⅓ per cent in all-day work means another reduction of 25 per cent of the operator-hours necessary to run the board, or a force equal to 75 per cent of the old force. Taking both these reductions into account makes the new operator-hours 47 per cent of the old. We may say, then, that with the automatic call distributor a manual board can be operated with less than half the operator-hours and less than half the operators that are now necessary with ordinary methods.

A Comparison. The advantages of the automatic traffic distributor over ordinary manual operation are most strikingly shown by direct comparison. In the following list the traffic conditions which reduce efficiency are given with the remedy which each system proposes.

General Hourly Variation

Ordinary Manual. Adjust number of operators to suit load. Greatly reduce efficiency at light load. Inferior service at overload.

Call Distributor. Adjust number of operators in exact proportion to load, each at full efficiency.

HOURLY VARIATIONS BETWEEN POSITIONS

Ordinary Manual. Use of intermediate distributing frame and team work.

Call Distributor. The difficulty does not exist—the load is equal on all.

MOMENTARY RUSHES, VARIABLE BETWEEN POSITIONS

Ordinary Manual. Team work.

Call Distributor. Uniform for all operators.

REDUCED EFFICIENCY WHEN TENDING MORE THAN ONE POSITION.

Ordinary Manual. Team work, but a very slight remedy.

Call Distributor. Difficulty does not exist, as each operator tends one position at all times.

From the foregoing it is seen that regarding every difficulty for which the ordinary manual has a partial and inadequate remedy, the automatic call distributor meets the issue squarely by removing the cause.

The automatic call, or traffic distributor, offers a very satisfactory intermediate step between manual and full automatic operation. If the human operator is to be retained at all, this system retains her services under the most favorable conditions. Those systems in which the operator is entirely cut off from the connection after it has been established, fail to secure the advantages of the much-talked-about human intelligence and personal touch. However, the writer is of the opinion that the human intelligence can be to advantage dispensed with, for the majority of telephone connections, and that full automatic will give a class of service superior to that of any other device which has so far been discussed.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 17, 1912.

DESIGN OF TELEPHONE POLE LINES FOR CONDITIONS WEST OF THE ROCKY MOUNTAINS

BY A. H. GRISWOLD

One of the most important portions of the outside plant of the companies engaged in the transmission of energy or intelligence is the structure for supporting the conductors, and as such it is receiving a constantly increasing consideration from engineers, as the value of an uninterrupted service at the least cost is being realized.

Of the companies using pole lines in the states west of the Rocky mountains, the Pacific Telephone and Telegraph Company undoubtedly has the most invested, encounters the greatest diversity of conditions, and covers more territory than any other company. For these reasons, this article will be devoted largely to the practises of this company.

WEATHER CONDITIONS

One of the most important factors in the design of pole lines is the variation in weather conditions, and in the region under consideration these conditions range from the mildest to the most extreme.

In Oregon and Washington, the destructive "pogonit" and "silver thaw" occur. The former is a weather condition encountered near Spokane, Wash. The word "pogonit" is an Indian name given heavy fogs which drift inland and freeze on cold exposed surfaces. The accumulation of ice on the wires sometimes to a diameter of about four in. (10 cm.) frequently causes complete failure, especially when followed by winds of high velocity.

The "silver thaw," while in many respects similar to sleet storms encountered in other parts of the country, is a name applied to a peculiar condition existing in Portland, Ore., and the near vicinity. Portland is situated at the junction of the Willamette and Columbia rivers. The winter climate of the Willamette valley is temperate while that of the Columbia valley is very severe. A very cold east wave passes down the Columbia valley and settles over Portland. This wave is usually of a temperature of from 5 to 22 deg. fahr. A southerly wind from the Willamette valley sweeps the moisture-laden clouds toward Portland, the clouds being deflected to the upper strata by the hills south of the city and over the cold air from the east. Precipitation then starts from the upper strata, freezing in passing through the cold lower strata and crystallizing on all solid objects. This condition has occurred in the past on an average of every four years since 1871 (before which time no records were kept). During this period, however, there have been only three storms which have been severe, those of 1881, 1907 and 1912. During the last storm all aerial plant in Portland was coated with from one-half to one in. (13 to 25 mm.) of solid ice. (See Figs. 1A and 1B).

On the Coast range and high Sierras, high winds, low temperatures, sleet and great depth of snow are experienced. In some portions, such as at Summit, Cal., the Government records show the annual average snowfall to exceed 36 ft. (10.9 m.) and occasionally the annual fall exceeds 65 ft. (19.8 m.) During long-continued storms the snow sometimes reaches a depth sufficient to cover the entire pole line, (see Fig. 2), burying it under many tons of snow. During subsequent changes of weather conditions a crust forms and gradually sinks, crushing the whole line by sheer weight.

In the southeastern portion of California, embracing the territory of the San Bernardino and Colorado deserts, one of the highest ranges of temperature in the United States occurs. Government records show that the annual range of temperature in that region varies from the freezing point to over 130 deg. fahr. A temperature of over 140 deg. has been reported. Such great temperature changes make it necessary to exercise great care in stringing the conductors. An exact relation between sag and temperature must be maintained to prevent dangerous stresses arising during subsequent falls in temperature.

On the mountains bordering the Pacific coast, and especially along certain exposed portions of the coast, high winds are

[GRISWOLD]

FIG. 1A—EFFECT OF SILVER THAW, PORTLAND, OREGON, 1912, ON OBSOLESCENT POLE CONSTRUCTION

[GRISWOLD]

FIG. 1B—EFFECT OF SILVER THAW, PORTLAND, OREGON, 1912, ON MODERN STANDARD TOLL LINE CONSTRUCTION

[GRISWOLD]

FIG. 2—HEAVY SNOWFALL AT CISCO, CAL., SHOWING SAN FRANCISCO-RENO TOLL LEAD AND SOUTHERN PACIFIC SNOW SHEDS

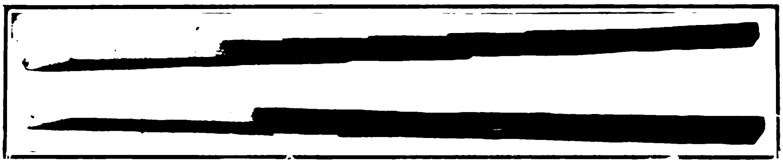


FIG. 3—SHOWING EROSIVE ACTION OF SAND STORMS [GRISWOLD]

FIG. 4—GENERAL VIEW OF TESTING APPARATUS [GRISWOLD]

encountered. On the eastern edge of the mountains bordering the western side of Death valley and the Salton or Colorado desert, the winds often reach the magnitude of a hurricane. High velocities are recorded annually during the months from October to March. Along the entire coast, and throughout the larger portion of Southern California, weather conditions of unusual mildness prevail. It is evident, therefore, that weather conditions as severe as any in the United States, as well as the most mild conditions, must be met in the design of pole lines.

POLES

Supply. Of the available supply of timber existing in any quantity west of the Rocky mountains, but three kinds are suitable for poles in the untreated form—Western red cedar, (*thuja plicata*) commonly known as Western white cedar, redwood (*sequoia sempervirens*), and Port Orford cedar or Lawson cypress, (*chamaecyparis Lawsoniana*). Due to the limited supply of the Port Orford cedar, it is not of much importance, notwithstanding its virtues. When open-tank or pressure preservative treatment becomes general, the field of available pole timber will be much widened by the use of such woods as lodgepole pine, yellow pine, Douglas fir, tamarack and other conifers.

With a few exceptions, redwood is used for poles only in the sawn form, and since redwood is used very extensively for structural purposes, the price depends upon the market price of redwood lumber, which fluctuates considerably. Unlike redwood, which is sawn from very large trees, cedar is generally used in its natural form. Inasmuch as the demand for poles is probably much more uniform than for lumber, and also because of the fact that the greater portion of the timber used for poles would be of little value for other purposes, the price of cedar poles is comparatively uniform. It is often economical to use sawn redwood poles where there is an excessive demand for any one size, because of the facility with which poles of a given size may be provided, and at the same time not react unfavorably on the price, as it would in the case of a heavy demand for a particular size of corresponding cedar poles. This economy was recently practised in the construction of a line from Banning, Cal., to Yuma, Ariz., where approximately 7000 redwood poles of the same dimensions were used—20 ft. (6.1 m.) long, 5 in. (12.7 cm.) tops, 9 in. (22.8 cm.) butts.

At present the supply of cedar poles is obtained principally from that part of Washington adjoining Puget Sound, because of the cheap water transportation to other points on the Pacific coast. There is still much available pole timber in the interior of Washington, Oregon and Idaho, which has not yet been drawn on to any great extent.

In many portions of the western timber country, there are large quantitites of fire-killed timber conveniently situated for water transportation. This timber has heretofore been considered worthless either for structural purposes or for poles, but from recent investigation it is thought to be as valuable for poles as live timber. It will probably come into extensive use in the near future, as it comprises about 15 per cent of the available pole supply. These poles are particularly adapted to treating because of their thorough seasoning.

Split cedar poles have a limited use in localities where small round cedar poles are not available. These poles are obtained by splitting larger trees where it is not economical to have them sawn. It is generally conceded that they are more resistant to decay than sawn poles, because the cells are not opened as in sawing. However, they are very unsightly and are not used where the appearance of the line is essential.

Destructive Influences. Of all factors which tend to influence the selection of a timber for pole work, the rate of butt rot is undoubtedly the most important. Even when exposed to the same conditions, the life of untreated poles of equal size may vary from two to twenty years or more, depending on the variety. However, if a pole could be obtained large enough, it could be designed for any reasonable definite life if the rate of rot could be determined.

The generally accepted theory of rot is that it is caused by a low form of life termed fungus which excretes substances which either dissolve or cause a gradual deterioration of the fibre of the wood. Many conditions enter to affect the rate of rot of a given pole, *i. e.*, the moisture, temperature, air supply, the food value to the fungi of the wood in question, nature of the soil, amount of drainage, and perhaps the stresses to which the pole is subject. The latter at first may not seem important, yet it has been noticed that corner poles, and poles subject to repeated shock, rot at a considerably more rapid rate than others, possibly due to fibre fatigue and the consequent lessening of the timber resistance to decay. The four essentials to rot, or the life of fungi, are air supply, moisture, warmth and food. The absence of any one of these will prevent decay.

The principle underlying nearly all preservative treatments is the removal of any one or more of these essentials. The difficulty of regulating the first three, *i. e.*, air supply, moisture and temperature, may readily be appreciated, but the removal of the food value may be accomplished by impregnating the timber with some toxic substance, such as creosote, zinc-chloride or copper sulphate. The latter two salts leach out quite rapidly, but the creosote will remain in the wood for quite an extended period, even when submerged in water, and is effective in preventing fungi from entering the wood.

The other agencies acting at the base or ground line of the pole, such as erosion, fibre fatigue, or chemical decomposition in the direct sense, are of little importance in the absence of fungi.

However, butt rot is by no means the only destructive influence encountered. In the San Joaquin valley, near Middle river, a section of line a number of miles in length has several times been burned by slow peat fires. If this trouble becomes more serious, it may be necessary to imbed the poles in a footing of loose gravel of sufficient thickness to prevent the heat from injuring the pole. For a short distance over the Yuma-Los Angeles line, after entering the desert country, the poles are subject to a sand-blasting action due to the sand carried by the strong winds. Fig. 3 illustrates the destructive effect of these storms on survey stakes which were in the ground for a period of only four or five months. Many remedies have been suggested, such as non-drying paint, which will collect a sand coating, metal sheathing, or some paint which would present a hard stone-like surface. For a number of years the Western Union Telegraph Company has protected its poles from this action by placing stubs on the windward side.

In addition to the conditions named, which work towards the destruction of pole lines, there are storms, fires, white ants, woodpeckers and other minor agencies.

Rate of Decay. As before stated, the life of any given pole is very uncertain. However, if a sufficient number of measurements are taken at the point where maximum decay occurs, a very close determination of the average rate of decay of any given wood may be determined for a given territory.

A very extended determination of the average rate of butt rot of Eastern white cedar has placed it at about 0.3 in. (7.6 mm.) in circumference per year as an average under all conditions.

That of Western cedar is probably approximately the same. However, steps are being taken to determine this rate accurately for the Pacific coast for redwood and Western cedar poles. The rate for redwood varies with the physical characteristics of the wood. Some portions of the butts (*i.e.*, "butt cuts") show remarkable resistance to decay, while sapling and "top cuts" often decay rapidly. The rate of decay of sawn redwood is now considered to be approximately the same as that of cedar, although this is probably too great, due to the fact that sawn redwood poles contain no sapwood.

In this connection, it might be interesting to state that the point at which decay proceeds most rapidly is just below the ground line for Eastern cedar, and about four to eight in. (10.1 to 20.3 cm.) below for Western cedar.

Strength of Poles. Realizing the importance of Western cedar and the necessity for definite information regarding its physical characteristics, the Pacific Telephone and Telegraph Company undertook to obtain the modulus of rupture or the ultimate unit outer fibre stress of poles used in the construction of its lines.

It is a well established fact that in order to obtain the true modulus of rupture of a given timber, actual structural timber must be tested. Since this is the first test performed in the West on poles in a manner closely approximating the conditions existing in the line, it may be of interest to describe somewhat in detail the methods of conducting the test and the conclusions drawn.

POLE TESTS

Specimens. Eighty poles were carefully selected as representative of the forest run used for pole work. They were of three classes—Western cedar from Idaho, Western cedar from Washington and Port Orford cedar from the western slopes of Oregon. From each of these three classes specimens were selected as follows:

Length		6-in. (15.2 cm.)	7-in. (17.7 cm.)	8-in. (20.3 cm.)	9-in. (22.8 c.m)
ft.	m.	top	top	top	top
25	7.6	3 or more	3 or more	3 or more	
30	9.1	3 or more	3 or more	3 or more	
35	10.6		3 or more	3 or more	3 or more

The Western cedar at the time of the test had been cut from one to eight years from live growing timber. The poles were about equally divided between summer and winter cut. The

Port Orford cedar had been summer-cut 23 months before testing from fire-killed standing timber. As would be expected from the length of time they had been cut, the poles were well air-seasoned. No consistent method was followed in seasoning, and consequently some poles contained very large weather checks, while others which received less rigorous treatment were in good condition.

Apparatus. Figs. 4 and 5 give a clear idea of the apparatus and its dimensions. The uprights were made of 12 in. by 12 in. (30.5 by 30.5 cm.) Douglas fir, thus making the apparatus very rigid. The conditions of actual service were duplicated as nearly as possible, the pole being inserted between the uprights six ft. (1.8 m.) from the butt, or at about the average ground line. The main part of the pole extended forward free from all obstructions to a metal covered platform where the end rested upon a metal carriage, which in turn traveled on the metal platform. The carriage was provided with easily running truck castors to facili-

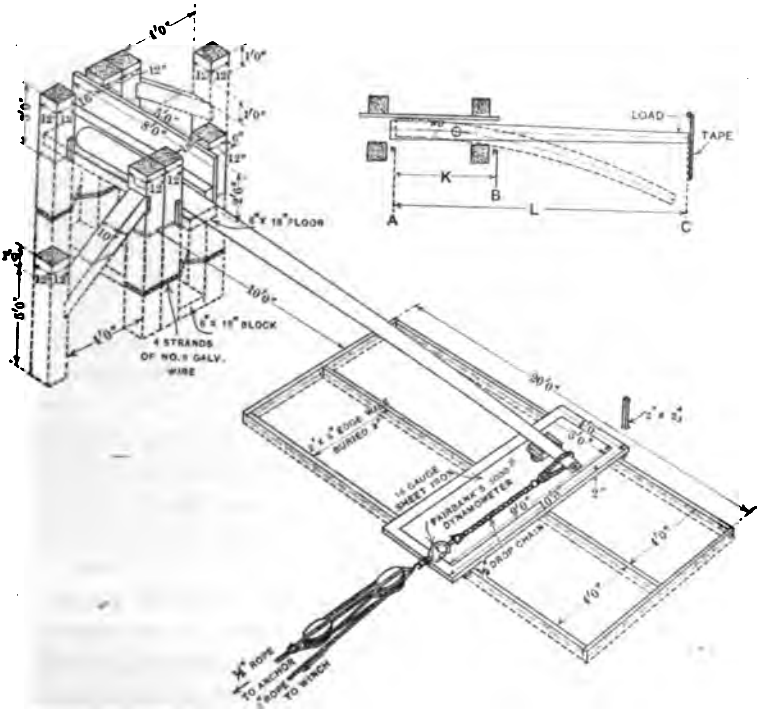


FIG. 5—ISOMETRIC DRAWING OF TESTING APPARATUS

tate its travel in a circular path. A constant pull of ten pounds (4.5 kg.) was necessary to overcome the friction of the carriage, final readings being corrected by this amount.

All deflection readings for the crushing of the pole at the butt and ground line, the movement of the machine and the top deflections were taken from stakes driven into the ground, and entirely independent of the machine. The top deflections were corrected for the crushing at the ground line and butt and the movement of machine by an amount equal to

$$D_b \frac{(2L - K)}{K}$$

where L = length of pole
K = distance between supports
D_b = movement of pole at B (See B, Fig. 5) due to crushing of wood and movement of support.

This formula applies only to the case where the movement at A and B is the same, which was found to be true in practically all cases.

The traction dynamometer was calibrated, the true reading being plotted against the observed reading. The winch and tackle gave a mechanical advantage of 150.

Method of Conducting Test. The test specimen was first carefully examined and noted for defects, such as injuries to sapwood from rough handling, grubs, worms, ants, bark trimmer's axes, weather checks, (star or ring), butt or top rot, large knots, an excess of sapwood or very irregular sections. The weight was obtained by the use of a pair of spring scales suspended from a tripod. The dimensions of the pole obtained were top circumference, butt circumference, circumference six ft. (1.8 m.) from the butt, circumference of the center, in inches, and the length in feet.

The specimen was then lifted into the machine, six feet (1.8 m.) of the butt blocked tightly against the uprights, and an initial tension put into the rigging to clear all obstruction. The length of the lever arm was then obtained.

The pole was deflected at the constant rate of one ft. (30.5 cm.) per minute until failure took place, deflection readings being taken at the top, ground line and butt for each load increment of 100 lb. (45.3 kg.) The top readings were taken from a nail driven into the center of the pole to avoid errors due to unequal fibre strain or rolling. After failure, the distances from the

PLATE XI
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[GRISWOLD]

FIG. 6—TYPICAL BREAK OF WESTERN CEDAR FROM IDAHO

[GRISWOLD]

FIG. 7—TYPICAL BREAK OF PORT ORFORD CEDAR

[GRISWOLD]

FIG. 8—TYPICAL BREAK OF WESTERN CEDAR FROM WASHINGTON

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[GRISWOLD]

FIG. 9—EFFECT OF AXE-CUTS IN LOCATING POINT OF FRACTURE

[GRISWOLD]

FIG. 10—SHOWING EFFECT OF EXCESS OF SAPWOOD, DUE TO RAPID GROWTH

point of fracture to the top and ground line were measured. The circumference at the point of fracture was calculated from the dimensions previously obtained. After examining the nature of the fracture and photographing, a one-in. (25.4 mm.) section to be used as a moisture sample was obtained as near the point of failure as possible. These sections were also used to obtain the rings per inch and percentage of sapwood. The samples were weighed immediately after cutting and again after being oven-dried to a constant weight, the percentage of moisture being then calculated in terms of the dry weight. Figs. 6 to 10 show typical fractures for the woods tested and the effects of the various defects encountered.

Calculations of Tests. The pole was treated as a tapered cantilever beam and the calculations for the modulus of rupture made by means of the fundamental formula, $S = \frac{M\,C}{I}$ assuming that this law holds to the point of rupture. In obtaining the volumes and weights per cubic foot, the pole was treated as a truncated cone.

Following are the data obtained, and curves, Fig. 11, show the comparative strengths of the timbers tested:

POLES 1-27 INCL.

WESTERN CEDAR (*THUJA PLICATA*) FROM IDAHO

Modulus of rupture (lb. per sq. in.)	Moisture content per cent	Sapwood per cent of total area	Rings per inch	Weight per cu. ft. (lb.)	Load at failure (lb.)
5,270	10.	26.	20.	22.7	2,214 (1,004.2 kg.)

POLES 28-51 INCL.

LAWSON CYPRESS OR PORT ORFORD CEDAR (*CHAMAECYPARIS LAWSONIANA*)

FROM WESTERN SLOPES OF OREGON

7,220	12.		16.	26.7	3,040. (1,378.9 kg.)

POLES 55-81 INCL.

WESTERN CEDAR (*THUJA PLICATA*) FROM OREGON AND WASHINGTON

5,350	15.	34.	12.	21.9	1,928 (874.5 kg.)

NOTE.—The per cent of sapwood was not calculated on Port Orford cedar because of the difficulty in differentiating between the heart and sapwood on many of the samples.

Conclusions from Tests. Weather checks are an important factor in the weakening of Port Orford cedar, and as in the case of red cedar, the more rapid the growth the weaker the pole.

The analysis of the cause of weakness of any pole was made difficult by the insufficient data on the history of the particular poles tested. The principal causes of weakness of Western red cedar, in order of their importance, seemed to be:

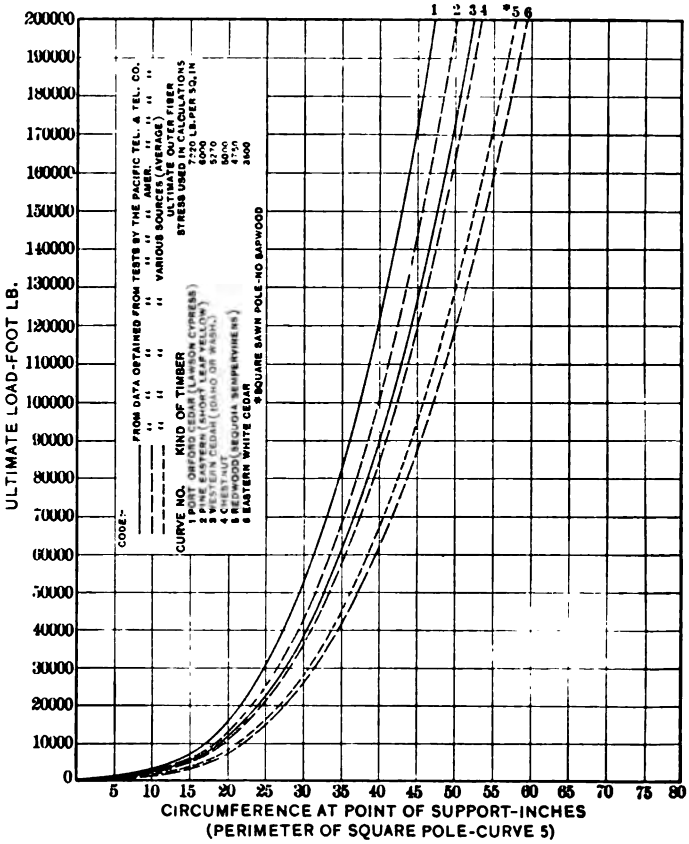

FIG. 11—COMPARATIVE STRENGTH OF POLE TIMBERS

1. Injury to sapwood { *A* Teredo pitting
   B Bark trimmer's axe cuts. (See Fig. 9)
   C Bruising
2. Rapid growth
3. Excessive sapwood (See Fig. 10)
4. Weather checks
5. Knots.

Injury to sapwood, although of very great importance in reducing the initial strength of the pole, has probably no bearing on the effective life. No center rot being encountered, conclusions were not formed as to its bearing on the strength of the pole.

Due to the low moisture content of the poles tested, no conclusions could be drawn as to the effect of moisture on the strength of poles. However, since poles used in line construction are generally cut several months before being set, they are usually moderately well seasoned and under such conditions the moisture content cannot be considered of any great importance.

The results of the tests of Port Orford cedar are far more consistent than those of Western cedar, due probably to the timber being more uniform in age and quality.

The data show definitely that the Western poles are not of an economical taper and that the ground line is the critical point.

In obtaining the data given above, only those poles which contained defects as listed in the specification adopted by the Pacific Telephone and Telegraph Company were discarded.

Classification and Specifications

The strength and rate of rot of poles are of fundamental importance in determining their life under a given load. The ultimate load to which the pole is subject may be determined with a reasonable degree of accuracy. The life assigned is dependent upon the increase of load necessitated by the development of the surrounding country, probable changes in equipment, new laws or ordinances affecting the construction and the economical life as determined by a cost study. With the life assigned and the load known, it is only necessary in order to obtain the original circumference at the time of setting to add sufficient wood to allow for the rot at the ground line during the life of the pole.

In drafting specifications for poles, it is desirable to utilize as great a portion of the forest run of poles as possible, in order that there shall be no reaction on the price due to the excessive demand for any particular size.

The following specifications based on these factors for Western cedar poles, with the classes assigned according to the importance and size of the line, will further illustrate the application of this principle.

Length of poles		*A* [Minimum top circumference 28 in. (71.1 cm.)] Circumference 6 ft. from butt		*B* [Minimum top circumference 25 in. (63.5 cm.)] Circumference 6 ft. from butt		*C* [Minimum top circumference 22 in. (55.8 cm.)] Circumference 6 ft. from butt		*D* [Minimum top circumference 18½ in. (47 cm.)] Circumference 6 ft. from butt		*E* [Minimum top circumference 15 in. (38.1 cm.)]	*F* [Minimum top circumference 12 in. (30.5 cm.)]
ft.	meters.	in.	cm.	in.	cm.	in.	cm.	in.	cm.		
20	6.1	30	76.2	28	71.1	26	66.0	24	60.9	No butt requirement	No butt requirement
22	6.7	32	81.3	30	76.2	27	68.6	25	63.5		
25	7.6	34	86.3	31	78.7	28	71.1	26	66.0		
30	9.1	37	94.0	34	86.3	30	76.2	28	71.1		
35	10.6	40	101.6	36	91.4	32	81.3	30	76.2		
40	12.2	43	109.2	38	96.5	34	86.3	32	81.3		
45	13.7	45	114.3	40	101.6	36	91.4	34	86.3		
50	15.2	47	119.3	42	106.7	38	96.5	36	91.4		
55	16.7	49	124.4	44	111.7	40	101.6	38	96.5		
60	18.3	52	132.1	46	116.8	41	104.1	39	99.0		
65	19.8	54	137.1	48	121.9	43	109.2				

The foregoing specifications do not require seasoned poles; however, it is preferable to use seasoned poles because of the lessened weight and subsequent lessening of the cost of freight charges and handling. Well seasoned cedar poles may lose from 20 to 35 per cent of the original weight, depending on the season in which they are cut. Autumn and winter cut poles will usually lose the greatest percentage of weight. A material increase of strength follows thorough seasoning. The weight of green poles varies from 34 to 39 lb. per cubic foot (545 to 625 kg. per cu. m.), while that of seasoned poles may be from 20 to 26 lb. per cubic foot (321 to 465 kg. per cu. m.).

The top size specifications in general use at present are entirely irrational inasmuch as the top size of a round pole is no indication of its desirability or life under a given condition. The taper may vary considerably on a given top size pole, depending upon the environment in which it was grown, the judgment of the cutter and many other uncertain factors.

The average circumference taper of Western cedar is slightly less than three in. (76.2 mm.) per 8 ft. (2.44 m.) of length, while that of Port Orford cedar is three in. in circumference per 10 ft. (3.05 m.) of length.

A pole of economical taper, disregarding decay, would be one that theoretically would not break at any one point, more readily than at any other point, *i. e.*, the unit stress of the most strained fibre would be a constant for any section of the pole. Since the strength of a pole increases as the cube of the diameter, an economical taper would require a pole of a taper that is probably never reached in practise. For instance, a pole seven in. (17.8 cm.) in diameter at the point of load would require about a 22-in. (55.9 cm.) ground line diameter if the load were applied 30 ft. (9.1 m.) from the ground line. In addition, butt rot is continually reducing the effective taper. Sawn poles have the advantage that any desired taper may be obtained at will, of course, within practical limits.

Pole Spacing. The spacing of poles varies greatly, and depends principally on the nature of the conductors, degree of exposure to the elements, and the factor of safety desirable.

The above specifications are based on about a 15-year life with a spacing of 130 ft. (39.6 m.) for 60 wires or less, and 120 ft. (36.5 m.) for 61 to 80 wires, and on the assumption that the line will be subjected to a wind of 50 miles per hour and a sleet load of ¼ of an inch (6.3 mm.) in thickness and that the conductors are all of the average size used in telephone line construction. If it is desired to increase the life of a line, the span is shortened, thus reducing the load per pole and obviating the necessity of increasing the size of the pole. Because of the increasing cost and relative importance of lines which exceed a capacity of 70 wires, the spacing is reduced from 120 ft. (36.5 m.) for 70 and 80 wires to 100 ft. (30.5 m.) for 70 wires, and 90 ft. (27.4 m.) for 80 wires, where severe weather conditions exist. This has been done to increase the life and reduce the liability to accidents, and thus bring the pole line in cost equilibrium with the remainder of the outside plant.

Where it is desirable to take advantage of local favorable conditions, this may be accomplished either by increasing the span or decreasing the size of the pole. The latter method would involve very little saving outside of the decreased cost of handling poles of lighter weight and the difference in cost of the smaller poles, except where a heavy demand for poles of a larger size would react unfavorably upon the price. The first method, however, presents several advantages, such as the saving of the first cost and erection cost of several poles per mile with the necessary fixtures, and may be adapted to make all portions of a line consistent with the varying degrees of exposure to the elements.

Because of the wide range of weather conditions existing in the Pacific Coast territory two spacings have been designed, one applicable to localities where severe weather conditions exist and another to regions of mild weather conditions. The considerable saving effected may readily be appreciated by the comparison of the two spacings.

	Ultimate Capacity		
	80 wires	70 wires	60 wires
Severe conditions	90 ft.–27.4 m.	100 ft.–30.5 m.	130 ft.–39.6 m.
Mild conditions	130 ft.–39.6 m.	155 ft.–47.2 m.	200 ft.–60.9 m.

It must also be understood that the spacing for mild conditions is less than would be theoretically possible, because of other limiting factors, such as greater relative importance of the larger lines, danger of swinging contact of wires and an endeavor to maintain the line in cost equilibrium with the remainder of the outside plant.

Replacement of Poles. Realizing the importance of uninterrupted service, and the variation of conditions affecting butt rot, a replacement inspection for pole lines has been provided. Although a line is generally designed for a 15-year life, the first inspection takes place eight years after erection and others every three years thereafter. It is the practise to allow the pole to reach approximately a safety factor of one before replacing. However, if the line is considered of unusual importance, or unfavorable conditions exist, a safety factor slightly greater determines the point of replacement. In order to introduce these factors and varying degrees of exposure to which a given line may be subject, replacement tables have been compiled, giving the minimum allowable circumference of sound wood at the ground line. The application of the replacement size necessarily is regulated entirely by the actual load upon the pole and not by the ultimate capacity.

LOADS

Except in lines carrying very heavy circuits, the column load may be disregarded and only the lateral wind need be considered in calculating the pole stresses due to wind loads.

The severity of conditions provided for may not necessarily be the most extreme that long experience has proved possible, as a cost study may prove definitely, for instance, that it may be more economical to assume the risk that the line may be wrecked before its economical life is reached rather than to build it sufficiently strong to withstand the maximum stresses possible over that period of time. In calculating wind loads, added surface exposed to the wind by the accumulation of sleet is one of the most important items to be considered. In order to avoid unnecessary complications, the column load is neglected, the pole and sleet-covered conductors considered as circular in section, and the wind as blowing horizontally and at right angles to the line. Under unusual conditions, the sleet may accumulate to a thickness of two in. (50.8 mm.). However, 0.25 in. (6.3 mm.) of sleet for small conductors and 0.5 in. (12.7 mm.) for large conductors are thought to be conservative amounts for which to provide. Wind velocities may exceed 100 miles (161 km.) per hour. However, a wind of 50 or 60 miles (80.4 or 96.5 km.) per hour is generally the maximum considered. Two types of weather conditions are considered—severe and mild,—the former governing the territory of probable sleet storms and wind velocities of 50 miles (80.4 km.) per hour or more, and the latter the territory where neither sleet nor winds exceeding 60 miles (96.5 km.) per hour occur. Fig. 12 is a copy of a map which was designed to show, in a general way, the blanket areas in which these conditions are encountered.

SAG OF WIRES

The calculation for the sag of wires is based on the equation of the catenary. The fact, however, that the conductor is an elastic material under tension must not be lost sight of when obtaining the result of a change in load. The component forces acting on a wire are the wind horizontally, the weight of the wire and the weight of ice or sleet vertically; the resultant of these represents the total force. The expansion and contraction due to temperature changes must also be considered. The general practise in calculating sag is to start with the most severe condition thought economical to assume, *i. e.*, maximum sleet, minimum temperature and maximum wind velocity and to assign the safety factor, generally 2. The sleet and wind loads are then considered as being released. This release of load reduces the tension in the conductor, which in turn contracts and lessens the sag. The lessening of sag again increases the tension and between the two conditions a point of equilibrium is reached. The conductor being now at the minimum temperature, the temperature is assumed to rise, causing the conductor to expand.

Here again the tension is released, and the conductor, due to its elasticity, contracts until a second point of equilibrium is reached for the temperature rise assumed. Thus the sag may be determined for any temperature.

With copper or other conductors with a large coefficient of expansion, it is well to obtain the sag at the various temperatures at which it is probable the wires will be strung. With other conductors, it is well to give them the benefit of the doubt by assuming that the maximum temperature exists when stringing.

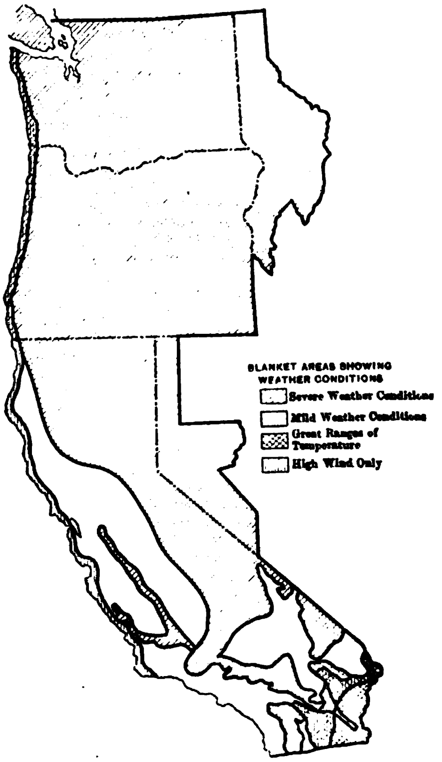

FIG. 12—MAP SHOWING GENERAL WEATHER CONDITIONS ON THE PACIFIC COAST

CROSSARMS AND PINS

The majority of the crossarms used in this territory are obtained in the Oregon and Washington district and are sawn from Douglas fir. This timber is cheap, strong and durable when used for this purpose and has been very satisfactory both in the untreated and treated form.

Locust pins are generally used due to their great strength and resistance to decay. However, the supply of this wood is limited, and experiments are being made on other kinds of wood by the Government in conjunction with the Pacific Telephone and Telegraph Company. These experiments have not been carried on a sufficient length of time to determine the relative merits of the woods under observation.

Guying

The problem of guying presents no features peculiar to this territory. The pole lines are designed to stand unassisted under the assumed conditions, and guys are placed either to afford an additional factor of safety or to cope with the local conditions which cannot be foreseen in the broad problem of design.

In general, guys are placed to accomplish one or more of the following purposes:

1. Supporting unbalanced stresses of conductors, due to dead-ending or change of direction.
2. Balancing loads caused by the attachment of foreign fixtures.
3. Preventing a local break from running each way along the line.

Cases 1 and 2 cover the placing of guys to meet unforeseen conditions, and case 3 affords an additional factor of safety.

Standardization

During the infancy of the telephone development in the Western States, the first cost was considered the main factor in the design of pole line construction, and the importance of reduction of maintenance cost and the continuity of service was not realized. Now, however, due to the realization of the importance of these factors, a great many of the early construction methods are either obsolete or obsolescent.

Many refinements have been introduced into pole line design which have had an important bearing on the economy of construction and maintenance. Naturally, the larger pole-using companies have been the first to put these practises into effect, but it is to be hoped that all companies will follow their lead, and that a very desirable standardization of materials and methods will result.

DISCUSSION ON "THE DESIGN OF TELEPHONE POLE LINES FOR CONDITIONS WEST OF THE ROCKY MOUNTAINS" (GRISWOLD), PORTLAND, ORE., APRIL 17, 1912.

H. Y. Hall: I ask Mr. Griswold what has been the experience of the telephone companies in the use of concrete particularly, and what has been the effect of the use of concrete on the butt rot. That is, under the weather conditions, applied under conditions similar to those in the west, and also in the different soils. The paper states " It is the practise to allow the pole to reach approximately a safety factor of one before replacing." Would that apply to all the poles in the line, or to just an occasional pole? I take it that it would be rather unsafe to apply a factor of one to a whole line of poles; you might to an occasional pole.

Gerald Deakin: Is the moisture content considered in determining the strength of poles when set? It is well known that the presence of moisture in timber weakens it, and for this reason, the strength of well-seasoned poles, as determined by the tests to which Mr. Griswold refers, would not give the actual strength of the poles when set in moist earth.

W. D. A. Peaslee: There was in the Sierras, in 1908, a pole with two crossarms, eight wires on each crossarm, on which the snow and sleet had drifted until the accumulated weight of snow on that pole was forty-eight hundred pounds outside of the weight of the wires. The Southern Pacific at that time ran two copper lines over the Sierras and uniformly along that line, from about Blue Canyon down to Truckee, the wire was found, next summer, to be much smaller in cross-section. The construction crew went over the line this next summer taking up this slack and practically a uniform decrease in size of about one gage number was found.

Gano Dunn: Why wouldn't it have been a good idea to leave it?

W. D. A. Peaslee: Because the next summer it would stretch another gage number and would be gone. They have one thing that comes in the Tahoe district along the Tahoe part of the line, that I have not seen or heard of in any other place. There is a green scale that forms on the copper wire in the course of two summers. When that was scrubbed off to get down to the copper, it was found one gage less in thickness. I have never heard of it in any other place and I would like to ask if anybody has.

D. P. Fullerton: Referring to the statement made by the previous speaker, I will say that the copper wires of the telephone company which are strung between Truckee and Lake Tahoe have shown the same condition, in that a green scale accumulates on the wires and apparently causes a reduction in the size of the wire. Nowhere else, so far as I know, have our wires been so affected. The lines crossing the Sierra Nevada mountains between Sacramento and Reno and which connect with the lines between Tahoe and Truckee at the latter place, and go through the same character of country, do not show this peculiar condition, although the lines are all exposed to the same general local conditions. No special investigation has been made to determine the source of this scale on account of the fact that the lines affected are rather unimportant circuits and only in use a portion of the year. We do find, however, that all copper lines strung through the Sierra Nevada mountains cause more or less trouble, in the form of shrinkage in the size of the wire and apparent loss of life of the copper due to extremely heavy snow falls that are encountered each year. We do not have the large number of wire breaks that would seem possible at first thought. The principal trouble is the weight of the snow which bears upon the crossarms and carries them from the poles; this being due principally to the heavy crust forming on the snow which settles on the arms as the snow melts underneath.

After a couple of years' study we have found that the life of copper wires, particularly the smaller gage wires, is apparently gone. Considerable study is being made of this, as stated in Mr. Griswold's paper. I will state that these lines were originally built with very little regard to engineering, but we are now giving these questions considerably more study and believe that a great many of our difficulties have been overcome.

P. M. Downing: Mr. Hall has brought up one question which I wanted to ask, *i. e.*, with reference to the life of the pole when set in concrete. There seems to be considerable difference of opinion as to whether or not the life is prolonged by the use of a reinforcing material of this kind. Of late we have all seen a great deal of literature describing different methods of preventing the decay of poles by placing concrete shells around them.

I understand that patents have been issued covering at least two different processes of this kind but so far as I can learn the only essential difference between them is in the kind of reinforcing metal used and the manner of placing the concrete.

I have heard it claimed that a pole would rot only at or near the surface of the ground and not near the bottom of the pole where the air was excluded. On this assumption it has been claimed that it was unnecessary to cover the entire butt of the pole with concrete but that a section for perhaps eighteen inches or two feet below the ground level was all the protection needed. My experience has been that in some localities or some kinds of soil a pole will rot near the surface of the ground and not at the bottom of the pole, while in others the rotting will start at the butt end and work up.

There seems also to be a question as to when it is best to put on this concrete shell. One advocate recommends concreting when the pole is set regardless of whether it is thoroughly seasoned or not. Another recommends that the pole be allowed to stand a few years until it has become thoroughly seasoned, or even until a portion of the sap wood has rotted, before concreting.

In California we have a great deal of trouble getting seasoned poles. Most of the poles used come from Oregon, Washington and Idaho and when received are either filled with sap or are water-logged to such an extent that it is inadvisable to attempt to treat them with any preservative.

I would like to ask the author of the paper whether or not he has ever had any experience along these lines and, if so, what the result has been.

S. J. Lisberger: I ask Mr. Griswold if the telephone companies have used any poles coated with creosote, and if a particular class of soil has any effect upon a creosoted pole. I also ask if any copper clad wire has been used and what the condition of this wire is in comparison with the ordinary copper or iron wires used in that territory?

D. P. Fullerton: There is one point possibly Mr. Griswold may overlook and that has a bearing on Mr. Downing's questions, that I would like to mention. In his paper he refers to "peat" fires in the vicinity of Little river in the San Joaquin valley, California. We were troubled there with the poles being burned off below the ground line, and with no sign whatever above the ground line that there was any trouble, consequently, with a long and heavy line, we experienced quite a little trouble. I simply mention this to say that in making some experiments in replacing these poles, we enclosed them with a cement jacket, probably a half an inch in diameter, allowing the concrete covering to extend six or eight inches above the ground line. After the poles had been in place about two years, upon investigation and inspection we found that while this treatment had prevented the burning off of the poles by subsequent fires, and the concrete shell was intact, the rot increased at a greater rate than on unprotected poles that had been placed in the same locality a great many years ago.

A. H. Griswold: Answering Mr. Hall's question, our experience has shown that it is not good practise to concrete the butts of untreated poles. We have not had any experience with treated poles, but on untreated poles set in this manner butt rot may take place very rapidly, and on one particular lead of poles in the San Joaquin Valley, as indicated by Mr. Fullerton, the life of the poles was decreased between 50 per cent and 75 per cent.

The use of reinforcing concrete collars to which Mr. Downing refers is open to the same objection of butt rot as outlined above, and in addition may be mechanically weak and very costly.

Replying to Mr. Hall's question concerning the safety factor of one that is applied to each pole: the replacement inspection is made on each pole and the lead is not considered as a whole, but each pole is taken as a unit of that lead.

A safety factor below one is sometimes allowed. This safety factor takes into consideration the wind velocity and ice load wherever it may occur. In allowing the safety factor of a lead to fall below one you are simply taking a chance that the maximum wind or ice load will not occur before the final replacement of the pole.

In the same connection Mr. Deakin asked whether the moisture content was taken into consideration in the replacement inspection of the poles. I understand that it is indirectly taken into consideration in compiling the replacement tables.

Answering Mr. Lisberger, there isn't any doubt but that the class of soil affects the butt rot of poles.

If the resistance in each alternator circuit is comparatively large so that the variation in the copper losses should not be neglected, a solution can be obtained if it be assumed that the speed-load characteristics of the prime-movers are identical and that the rotational losses are constant. In this case the powers supplied to the alternators are equal, and any difference in the outputs can only be accounted for by a corresponding difference in the copper losses. This gives the relation

$$\frac{I_0'}{I_0''} = - \frac{r\,I''}{V + r\,I'}$$

in which I'_0 and I_0'' are respectively the energy and wattless components of the interchange current with respect to the terminal voltage V, and I'' and I' are respectively the wattless and energy components of the current supplied to the load with respect to the terminal voltage V. r is the armature resistance of one generator. The minus sign has this significance: if the load is inductive the power supplied by the alternator will increase as the excitation is diminished.

This relation shows that with a load of unit power factor, such as Mr. Welsh assumes, the interchange current is wattless with respect to the terminal voltages and the generators still continue to deliver equal powers in spite of differences in field excitation. This conclusion has been verified in the electrical engineering laboratory of the Massachusetts Institute of Technology for the case of two 15-kw. generators. It is only when the power factor of the load is other than unity that changing the excitations can cause a shifting of the load from one alternator to the other. As an example of the amount by which the load may be shifted by change in excitation take the following case:

With full load current let the Ir drop in one alternator and line to the point of parallel connection be 15 per cent of the terminal voltage. Assume that the load is inductive and requires twice the full load current of one alternator at 0.707 power factor, and that the interchange current produced by change in excitation is equal to the full load current.

Then

$$\frac{I_0'}{I_0''} = \frac{0.707 \times (2 \times 0.15)}{V + 0.707 \times (2 \times 0.15)} = 0.17$$

Thus the alternator with the smaller excitation will take 58 per cent of the total load and one with higher excitation will take 42 per cent of the total load.

The power transferred from one alternator to the other by governor adjustment which causes an angular displacement of δ in the internal voltages E is

$$P = V^2 \left(\frac{x_s}{z_s^2} + \frac{X}{2\,X^2} \right) \tan \frac{\delta}{2}$$

in which V is the constant terminal voltage of the alternators, x_s and z_s are the synchronous reactance and impedance of one alternator, and X and Z are the equivalent reactance and impedance of the load supplied. In this case it is necessary to increase the internal voltages equally in order to maintain a constant terminal voltage.

The interchange current produced by this relative phase displacement is

$$I = \frac{E}{z_s} \tan \frac{\delta}{2}$$

The internal voltage E varies with the power factor since $\frac{E - V}{V}$ is the regulation of the generator.

This shows that for a given angular displacement of the internal voltage both the interchange current and the power transferred depend upon the power factor of the load, and the writer does not understand why Mr. Welsh makes a contrary statement.

This same equation for power transferred gives the synchronizing power when the displacement δ is produced by hunting, except that in this case the internal voltages are constant, and $\tan \frac{\delta}{2}$ should be replaced by $\sin \frac{\delta}{2}$. The equation now emphasizes the well-known fact that alternators operate better in parallel on an inductive load, since for a given angular displacement the power transferred from one to the other is greater.

The effect of increasing the ratio of resistance to reactance, as would occur when the alternators are paralleled through equal transmission lines, can also be determined from this equation and is, I believe, not in accord with the explanation given by Mr. Welsh of the effect of the resistance and reactance drops in the connecting transmission lines.

The case of two dissimilar alternators, which is practically the same as that of two equal alternators connected in parallel by lines with unequal constants, is not quite so simple from the analytical standpoint, but the general qualitative results are much the same.

H. Y. Hall: I certainly do not agree with some of the conclusions reached in this paper. I agree somewhat with the criticisms that have been made in the discussion of Mr. Lyon. It is not possible in alternating-current systems by mere adjustment of voltage to shift the load from one machine to another, although it is possible in a direct-current system. In the alternating system the division of loads depends entirely on the characteristics of the governors, and a relative setting of the governors and the machines, and not upon a field adjustment. It would be possible to pull the field off the alternating-current generator and still carry the load, but if you pull the field off a direct-current machine, the current would increase. Otherwise the current would lag. It depends primarily on the setting of the field rheostat and the division of the load. That is borne out by practise. I have operated some of the largest stations in the country, and that is not only so in respect to the division of load between machines in one station, but is also true in respect to the division of load between two different stations running in parallel. I have in mind the 74th Street station of the Manhattan Railway and the 59th Street plant of the Interborough Rapid Transit Company.

Gano Dunn: Mr. Hall has contributed a very valuable item. I would suggest that where the question of stations is involved, and where there may be some considerable resistance between the stations, then there begins to come in the effect of load distribution due to change of excitation, other things being the same, but he has done us a valuable favor in pointing out that the real control of load distribution is not in the governor but in the rheostat.

P. M. Downing: I am inclined to take the same view of this matter as that of the last speaker. There is no question but that the division of load not only between generators of the same station, but also between different stations feeding into a network, must of necessity be taken care of by governor adjustment and not by field adjustment. With any fixed position of the governor, a certain amount of energy is delivered to the generator. This cannot be changed without changing the governor.

By adjusting the field you can change the form of the energy delivered by the generator, but you cannot change the amount. What really occurs when you change the field adjustment of any piece of synchronous apparatus operating in parallel with another is that you change the power factor on that machine; in fact the division of load and wattless current between stations feeding into any network are handled entirely independently of each other. On a network supplying power over a large territory, the power factor will be low and there will be considerable wattless current to be taken care of.

In the central part of California it has been the practise for several years past to operate a number of generating stations in parallel to feed a common network. At present there are 15 or 20 of these, the greater part of them being hydroelectric, with two or three steam turbine installations.

The total mileage of lines supplied is, approximately, 1500, exclusive of the low-voltage distributing circuits in cities and towns.

The steam turbines are located in the larger cities and while they run in on the general network with the hydroelectric plants, they ordinarily carry but little load. They are, however, often called upon to carry a full load of wattless current, and thereby serve as voltage regulators, and are always able to pick up the load in case of transmission line troubles.

A few years ago when the Pacific Gas and Electric Company constructed its first transmission line, there was but little demand for electric power, and the load was small. Considerable trouble was had with voltage regulation at the receiving end on account of the charging current of the line boosting the voltage.

This trouble was so pronounced that it became necessary to put in reactance coils to neutralize this leading current. With the increased power load and the resulting low power factor, it was found that not only was the leading current due to the capacity neutralized, but there was a heavy lagging current.

Today we have installed synchronous condensers where once stood the reactance coils. These machines are installed solely for regulating purposes. They are arranged to be operated automatically and are doing it so well that the voltage regulation has been greatly improved.

W. A. Hillebrand: With regard to this question of distribution of the load by means of field adjustments, Mr. Lyon has pointed out a case in the laboratory using two 15-kw. machines. He was able to make a difference in the adjustment of the load simply by field adjustments. It seems to me there is a marked difference where there are two machines in operation of perhaps equal capacity, constituting the only generators in the system, and which are operated at the opposite ends of the transmission lines. That case is quite different from the case where you have a large central station, or a large group of stations, and you attempt to swing the system simply by changing the field adjustment. It seems to me that it is possible to produce a certain adjustment of load where you have two machines of approximately the same capacity.

Lester McKenney (by letter): The paper by Mr. Welsh would have been of more practical importance had the subject of governor adjustment received the consideration which it deserves in a paper of this sort. With transmission lines and station circuits as usually constructed the question of satisfactory parallel operation resolves itself into one of governor adjustment, assuming that the units have been properly designed.

In order to insure proper division of the load between the generators operating in parallel on a system, the governors of the prime movers are adjusted for a definite drop in speed from no load to full load. Two per cent may be taken as a fair value. With this adjustment of the governors, neglecting the I^2R losses in the line, the division of any additional load thrown on the system is independent of the line or circuit constants. It will be evident that there must be a certain speed and governor position for any specified load. If the circuit between two generators consisted principally of resistance, and we should attempt to transfer load from No. 1 to No. 2 by rheostat adjustment, we would find that No. 2, in order to take more load, would have to slow down in order that the opening of the valves or gates of the prime mover might be increased andt he additional power required supplied. No. 1, upon dropping part of its load, would have to speed up to reduce the valve or gate opening in order to reduce the power supplied to the amount required by the remaining load. Such slowing down of one unit and speeding up of the other would be impossible if the resistance of the connecting circuit was such that parallel operation would be possible. The transfer of load from one generator to another by rheostat adjustment, when the governors are adjusted for satisfactory parallel operation, is, therefore, impossible.

With the governors adjusted for constant speed from no load to full load, and with the connecting circuits consisting principally of resistance, the transfer of load from one generator to another by rheostat adjustment is possible, and I assume that this is the governor adjustment which the author has in mind. The division of the load between the generators may also be materially affected by the line resistance and reactance. The transfer of load by rheostat adjustment, and the effect of the line resistance and reactance upon the division of the load would, under these conditions, be lost sight of in the erratic fluctuation of load caused by the lack of any tendency to load division on the part of the prime movers. Due to this erratic fluctuation of load the parallel operation of generators with governors so adjusted is unsatisfactory.

With the governors adjusted for a rise in speed from no load to full load parallel operation would be impracticable.

If the governor of one of two or more generators operating in parallel is adjusted to increase the gate opening, the generator must necessarily take more load, independent of the circuit conditions, otherwise the generator would speed up and pull out of synchronism. In making this adjustment, the speed of the entire system is slightly increased.

Referring again to the connecting circuit consisting principally of resistance and considering the case where the governors are adjusted for a drop in speed from no load to full load, it is evident, from a study of the polar diagram, that when it is attempted to transfer load by rheostat adjustment, the generators automatically adjust the phase displacement of their electromotive forces, the electromotive force of the generator tending to drop its load advancing in phase; so that a resultant electromotive force is produced which will cause the current in the local circuit to be displaced 90 deg. from the induced electromotive forces. Should the resistance so far exceed the reactance that the 90 deg. displacement could not be obtained, the generators would drop out of synchronism.

The paper by Mr. Welsh does not, therefore, disclose any new methods of adjusting the wattless current and load on generators, working under practical operating conditions.

J. W. Welsh: The subject matter of this paper was suggested by the experience of the writer in the load dispatching system of the Pittsburgh Railways Company. We had there two plants operating in parallel, one of about 4000 kw. and the other of about

21,000 kw. capacity. It is the duty of the load dispatcher to distribute the load between these two plants and order on and off machines at substations which are fed from these plants according to the variations of the load. He also directs the setting of the busbar voltage at each plant. The busbar voltage is controlled by an automatic regulator and of course the speed is controlled by governors. It was noticed in the operation of this system when the busbar voltage was raised at one plant, that it was possible to shift the load between the two stations. These plants are connected through three cable lines, that is, they operate in parallel over three separate circuits to which the load is independently connected. I had always been of the opinion that it was impossible to produce any definite transfer of the load without going to the governors and making a change in the setting of them. We found, however, that a transfer of load occurred when the busbar voltage was changed by field adjustment.

I believe the criticism of the fact that it is possible to cause a transfer of load by field adjustment is due to a misconception of the point of view of the writer in this paper, and that is this: It is of course obviously impossible to make a machine at one station carry more load without giving it the necessary driving power for the increase in load. In other words, it is necessary that there should be a change in governor setting to carry any increase in load that may come to that station from any other cause. That is explained in the paper. The engine or turbine governors at each station, being automatically controlled, at once admit the necessary steam at the station receiving more load, and decrease the steam admitted at the station from which the load is taken. The assumption is made that the phase angle doesn't change and that the necessary steam is admitted by such change in governor setting as is required to prevent any change in phase angle of the electromotive forces. If you hold the phase angles constant then a change in field adjustment as shown by the diagrams will bring about a transfer of the load. Of course that is a situation that does not occur very often and only occurs to a limited extent. In other words the change in load by field adjustment is in proportion to the resistance component of the cross current; and that is usually a minor component, particularly on a transmission line where the inductive reactance is high. On a cable system, however, the resistance is usually higher than the reactance. In our case, the paralleling circuit is a cable between stations.

R. Howes: I would like to ask Mr. Welsh regarding the load-speed curve of the governors which he used. Were the governors designed for a flat speed at all loads, or how much reduction in speed was there from no load to full load?

J. W. Welsh: I am not able to say definitely. I imagine about 4 per cent, but I may say these diagrams are merely made to represent pictorially what happens; in every case, it is possible of course for the attendant to change his governor setting as the load changes, but that was unnecessary in the case I spoke of where the change is secured in the load by field adjustment. I am not sure that 4 per cent is the actual amount.

F. K. Brainard (communicated after adjournment): Mr. Welsh concludes, among other things, that a change in relative field strength of two alternators in parallel may change the distribution of load between them. If he refers to the case in which the machines are constrained to operate in synchronism through some other condition than merely paralleling them electrically, *e.g.*, if the rotors are mounted upon the same shaft or if they are driven by synchronous motors which take current from the same source, then the following criticism does not apply. Also, he may have in mind the slight change in efficiency due to a change in power factor. This will usually be too small to observe, however, and probably he does not refer to this. But with these possible exceptions, the writer cannot agree with him in the conclusions which he deduces.

For every prime mover with its governor, there is a certain definite relationship between speed and power delivered, and for machines which are to operate alternators in parallel, the governors *must* be adjusted so that the speed will decrease as the load increases (unless the governors are interlocked). Hence, if the load increases on one unit, it must increase on *all others* in parallel with it. In other words the problem is entirely a mechanical one if the machines stay in synchronism, and the electrical conditions have nothing to do with the distribution of load between them. However, the question as to whether parallel operation will be satisfactory or not, is largely an electrical one, and as Mr. Welsh states, a certain amount of inductance is necessary, although on the other hand too much inductance may cause the machines to fall out of step because of insufficient synchronizing power.

The following is an attempt to determine in a general way the design of transmission lines over which parallel operation is contemplated.

Consider the case of two alternating-current plants, each serving its own load through separate feeders but connected in parallel by means of a tie line. The problem is to determine the relationship between the resistance and reactance necessary to give the best results. If the amount of power transmitted is small compared with the maximum capacity of the line, it can be easily shown that the value of reactance x which gives the maximum "synchronizing power" (*i.e.*, the maximum kilowatts per degree displacement of station voltages) for a fixed resistance r and for equal generator and receiver voltages, is $x = r$. (See Note 1.) Also, it can be shown that the value of reactance which gives the maximum capacity to the line (capacity for the transmission of power) under the same conditions is $x = \sqrt{3}\,r$. If the generator and receiver voltages are unequal but constant, the ratio of reactance to resistance which will make the capacity of the line maximum with a *fixed resistance* depends upon the ratio of generator to receiver voltage, as shown by the curve Fig. 1 of this discussion. (See Note 2.) In this and also the previous discussion the drop due to static charging current is neglected. Generally it will be negligible since the charging current is supplied from both ends of the line, but this is not always true. Hence it would seem that the best value for x is usually between $x = r$ and $x = \sqrt{3}\, r$.

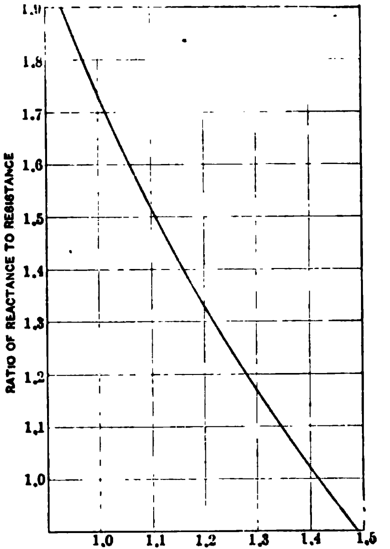

FIG. 1 — RELATION BETWEEN RESISTANCE AND REACTANCE TO GIVE THE MAXIMUM CAPACITY TO A TRANSMISSION LINE HAVING A FIXED RESISTANCE AND FIXED GENERATOR AND RECEIVER VOLTAGES

Electrostatic capacity not taken into consideration, *i.e.*, the effect of charging current is neglected.

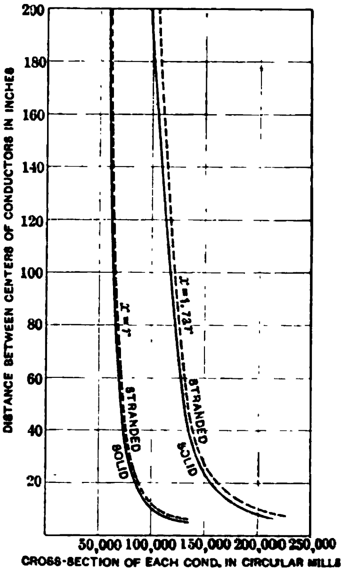

FIG. 2 — SPACING OF TRANSMISSION LINES AS DETERMINED BY RELATIONSHIP BETWEEN RESISTANCE AND REACTANCE AT 60 CYCLES

Of course the practical conditions will seldom be as simple as those assumed and the results would have to be modified accordingly. If automatic voltage regulators are not installed, the generator reactance should be considered as line reactance, and if regulators are installed which increase the voltage with the load a larger value of reactance should be used in the " tie line " than would otherwise be desirable. Similarly, a smaller amount would probably be desirable in circuits feeding shunt synchronous converters and a larger amount should be installed in the case of over-compounded converters. Also, if the tie line is a short one where heating rather than the point at which the stations "drop out of step" limits the capacity, the reactance should preferably be much greater. Dr. Steinmetz has stated that it should be no less than two times the resistance, and apparently he refers to this case. The greater the reactance, the higher will be the power factor of the cross current, and so for this case a larger reactance can profitably be employed.

If line inductance alone is to be relied upon to give the necessary reactance, the wires should be spaced according to the curves* shown in Figs. 2, 3 and 4. But in order to keep to practicable spacings, the sizes of conductors to be used are quite limited. Thus, for 60 cycles the range is from about No. 2 to No. 100, for 40 cycles from about No. 0 to No. 0000, and for 25 cycles from about No. 000 to 350,000 cir. mil.

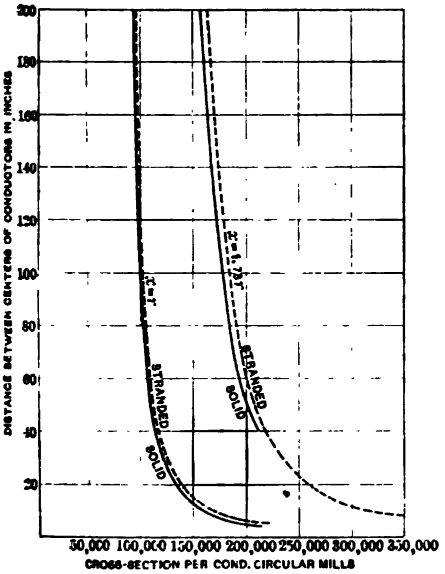

FIG. 3—SPACING OF TRANSMISSION LINES AS DETERMINED BY RELATIONSHIP BETWEEN RESISTANCE AND REACTANCE AT 40 CYCLES

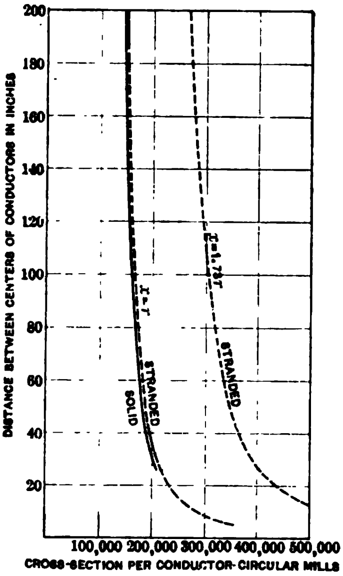

FIG. 4—SPACING OF TRANSMISSION LINES AS DETERMINED BY RELATIONSHIP BETWEEN RESISTANCE AND REACTANCE AT 25 CYCLES

Hence, it is seen why so little difficulty has been experienced

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* Curves in Figs. 2, 3 and 4 are for a three-phase line consisting of three conductors arranged at vertices of an equilateral triangle. Solid lines are for solid copper wire, dotted for stranded.

in paralleling 60-cycle systems of moderate power over long distances, and also why it has frequently been impossible to operate similar 25-cycle systems in parallel without the installation of additional inductance.

NOTE 1. To find reactance which will give the maximum synchronizing power for small displacements:

Let $E_0 = e =$ Receiver voltage.
$I_0 = i + j i' =$ Line current.
$r - j x =$ Line impedance.
$E =$ Generator e.m.f.
$\phi =$ Phase displacement between generator and receiver voltages.

Then (neglecting the charging current)

$$E = E_0 + I_0 (r - j x)$$
$$= e + i r + i' x + j(i' r - i x)$$

$$\tan \phi = \frac{i' r - i x}{e + i r + i' x}$$

If $E = E_0$ and the phase displacement is small, the following is approximately true:

$$i r = -i' x$$

$$\phi = \frac{i' r - i x}{e}$$

Hence

$$\phi = -\frac{\dfrac{i r^2}{x} + i x}{e}$$

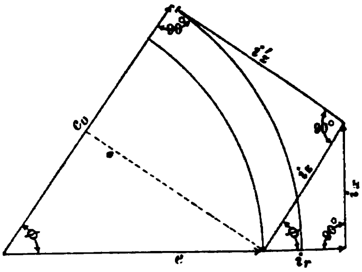


FIG. 5

If $W = ei =$ power delivered, then W/ϕ is a measure of the synchronizing power.

$$\frac{W}{\phi} = \frac{e^2}{x + \dfrac{r^2}{x}} = -e^2 \frac{x}{r^2 + x^2}$$

To find the value of x which will make W/ϕ maximum, r being constant, we put

$$\frac{d\left(\dfrac{W}{\phi}\right)}{d x} = -e^2 \frac{(r + x)\ (r - x)}{(r^2 + x^2)^2} = 0;$$

hence $x = r$.

NOTE 2. To find the reactance which will make the capacity of the line maximum when the generator and receiver voltages are constant but unequal:

Let e = Receiver voltage.
e_0 = Generator "
$\frac{e_0}{e} = a$
i = Energy component of current at receiving end.
i' = Wattless " " " " " "
ϕ = Angle between generator and receiver voltages.
r = Resistance of line.
x = Reactance of line.

Then from Fig. 5,

$$i\,r = e\,(a - \cos\phi)\cos\phi$$

The capacity of the line will be maximum when i is maximum. Hence, to find the phase displacement corresponding to this condition, we put $\frac{d\,i}{d\,\phi} = 0$

Hence

$$\frac{d\,i}{d\,\phi} = \frac{e}{r}\,(2\cos\phi\sin\phi - a\sin\phi) = 0$$

$\cos\phi = \frac{a}{2}$ is the solution which makes the function maximum.

But, from the figure, $\phi = \tan^{-1}\frac{x}{r}$

hence

$$\frac{x}{r} = \sqrt{\left(\frac{2}{a}\right)^2 - 1}$$

A. S. McAllister (communicated after adjournment): Without attempting to criticise in any way the accuracy of the diagrams shown by the author in so far as they represent conditions assumed by him, attention should be called to a highly important feature ignored by him, which nullifies his conclusions that by proper proportioning of the voltage of each unit by field adjustment it is possible to alter materially the sharing of load between generators operating in parallel. Quite independent of the electrical characteristics of circuits joining any two generators, the actual load supplied by each generator to the electrical system—including its own circuits—depends solely upon the power delivered to the generator by its prime mover. This relation is fundamental, in that it is based on the law of conservation of energy—the one law the accuracy of which engineers have as yet not been bold enough to question. When two generators are operated in parallel or are connected to a common system, the division of the load carried by these two generators depends upon absolutely nothing other than the adjustment of the governors controlling the power supplied by the prime movers; it is not affected in any respect by voltage adjustment or resistance of the interconnecting circuits. The only effect that can be attributed to the resistance of the circuit interconnecting the two generators is that relating to the efficiency of the transmission. Of the total amount of power supplied by the two generators a part is dissipated in resistance of the interconnecting circuits, and this part may be supplied in whole or in part by one or the other of the generators, according to existing conditions, such as the relative voltages of the units; but the sum total of the power supplied by each generator is determined solely by the amount of power delivered to it by its prime mover.

In every case where a derived result is found to be contrary to the law of conservation of energy, it is safe to assume that at least one error has been introduced in the assumption or calculations. In the present case the author seems to have ignored the fact that the time-phase position between the voltages of the two generators in parallel and the currents in the system must at each adjustment be such as to allow each generator to supply to the system an amount of power equal to the amount delivered to it by its prime mover. All other quantities must adjust themselves to correspond to this one fundamental requirement.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 18, 1912.

PLANT EFFICIENCY

AN ANALYSIS OF THE LOSSES OF A HYDROELECTRIC SYSTEM

BY J. D. ROSS

The following paper is an analysis of the losses and efficiencies of the Seattle Municipal Light and Power plant for the year 1911.

Great care has been taken in these measurements and the results have been checked in as many ways as possible and instruments have been frequently calibrated. These figures are therefore believed to be a close approximation to the true values.

GENERAL DESCRIPTION OF PLANT

The Seattle plant is a hydroelectric system delivering water to two 1,500-kw. Pelton units and two 5,000-kw. turbine units under 600-ft. (183 m.) head through two pipes approximately 3½ miles (5.6 km.) long, one of which is 67¾ in. (172 cm.) and the other 49 in. (124 cm.) inside diameter. The current is transmitted at 60,000 volts through two lines to Seattle, a distance of 38.7 miles (62.2 km.), and is there distributed at 15,000 and 2,400 volts for use by approximately 20,000 customers and for the city street lighting.

Pipe Lines and Penstocks. The 67¾-inch (172-cm.) pipe consists of 15,865 ft. (4,835.6 m.) of wood stave pipe, dividing at a point 951 ft. (289.8 m.) from the power house into two 48-in. (122 cm.) riveted steel penstocks. The 49-in. (124 cm.) wood pipe joins onto a 48-in. (122 cm.) riveted steel penstock at a point 1,008 ft. (307.2 m.) from the power house.

Careful tests were made on the 67¾-in. wood stave pipe, using gages calibrated before and after. The pipe contains five steel elbows, where the curvature is greater than 20 deg. These elbows are made to a 15-ft. (4.57 m.) radius and have angles respectively 92, 55, 60, 65, and 45 degrees. The loss in head of each elbow was measured by a differential pressure gage. The results of the test are given in detail in the following table:

LOSS OF HEAD IN FEET IN VARIOUS PARTS OF 67¾-IN. (172 CM.) WOOD STAVE PIPE

Velocity in ft. per second	Loss in entry and screens	Elbow No. 1 92°	Elbow No. 2 55°	Elbow No. 3 60°	Elbow No. 4 65°	Elbow No. 5 45°	Total loss in pipe	Friction loss after deducting entry and elbows	Loss in 67¾" stave pipe per 1,000 feet	Value of C in Kutters formula	Value of N in Kutters formula
2½	0.06	0.03	0.03	0.03	0.03	0.01	4.1	3.91	0.246	134.06	0.01190
5	0.25	0.09	0.08	0.08	0.08	0.05	15.4	14.77	0.931	137.96	0.01175
7½	0.54	0.25	0.18	0.19	0.20	0.14	33.9	32.40	2.0425	139.71	0.01165
10	1.14	0.46	0.34	0.36	0.37	0.27	61.9	58.96	3.775	137.01	0.011865

NOTE: 1 ft. =0.3048 m.

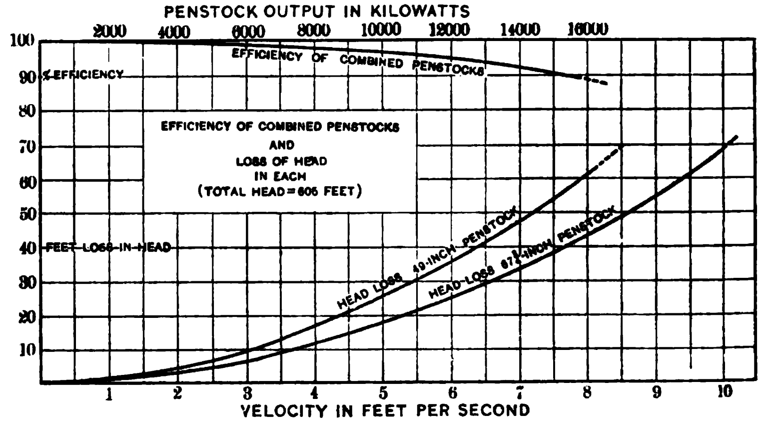


FIG. 1

This pipe has been in operation since November 20, 1908. The loss in entry as given in the above table seems large and rises with the velocity more rapidly than it should. This is apparently due to the resistance of the screens, which are of wood bars. These were being changed at the time the test was made as it was noticed at times of heavy load that there was a difference of level on the two sides of the screens. The entry of the pipe is bell-mouthed. The total length of the wood pipe is 15,865 ft. (4,835.6 m.) The line was designed for a slope of four feet per thousand feet to give a velocity of ten feet (3.05 m.) per second.

The loss in the penstocks was computed from records taken by recording gages at the generating station, which were frequently calibrated. The results so obtained were checked by computing the loss from the efficiency shown under test, and agreed very closely. The maximum output of the two penstocks was 12,400 kw., with a loss of 6 per cent, and the average output for the year was 6,009 kw., with an average loss of 2.3 per cent. This loss was increased by the fact that the plant was supplied for thirty-three days in November and December by the larger pipe alone.

Generating Station. There are four units in the power house, two of which consist of 8,000 h.p. Francis turbines direct-connected to 60-cycle, 2,300-volt, three-phase generators rated at 4,000 kw. at 35 deg. cent. rise, with a four-hour overload capacity of 5,000 kw. at 40 deg. cent. rise. These units operate at 600 rev. per min. The other two units are driven by 2,400-h.p. Pelton impulse wheels direct-connected to 60-cycle, 2,300-volt, three-phase generators rated at 1,200 kw. at 35 deg. cent. rise, with a four-hour overload capacity of 1,500 kw. at 40 deg. cent. rise. These units operate at 400 rev. per min. The wheels are each equipped with two runners, each of which is supplied from a needle and a deflecting nozzle. The combined capacity of the present installation is therefore 13,000 kw. on a 40 deg. cent. rating. The two machines last mentioned, however, exceed their rating and have been operated continuously without excessive heating at 1,750 kw., making the combined capacity 13,500 kw. Three waterwheel exciter units are installed, two of which have a capacity of 75 kw. each, and the third 150 kw.

As the efficiency of each unit varies with the load, and it is obviously impossible to have all generators that are in use at any time carry their full load, the all-day efficiency of the generating station will depend on the number of units in use and the load which each carries, as well as on the power factor of the load and, in the case of this plant, where two types of wheels are used, it will also depend on the proportion of the load that the operator gives to each type of machine. In general, the greatest all-day efficiency can be had by keeping the machines as nearly as possible at the load of maximum efficiency, and by shutting down the machines without load as far as can conveniently be done.

While the combined maximum efficiency of generator and wheel was found in the case of the 5,000-kw. units to be 76.7

per cent, and in the case of the 1,500-kw. units to be 69.9 per cent, the all-day efficiency of the plant for 1911 was found to be 56.7 per cent. This does not include current for excitation and station lighting. By including this as a loss, the all-day efficiency of the plant drops to 55.7 per cent.

The reason for the difference in the same type of unit is found in the fact that the operators favor No. 1 and No. 4 machines, from habit rather than intention. The impulse wheels, being small, are operated under full load for a great part of the day and their all-day efficiency is greater than that of the turbines, notwithstanding the higher efficiency of the turbine sets at full load. It will be readily seen from these facts that the efficiency of a plant depends very largely on the way it is handled by the operator and during low water periods it is possible to prepare a schedule showing which machines should be used for each load which the plant carries. This schedule will be modified by the conditions of the plant, changes in load, and regulation.

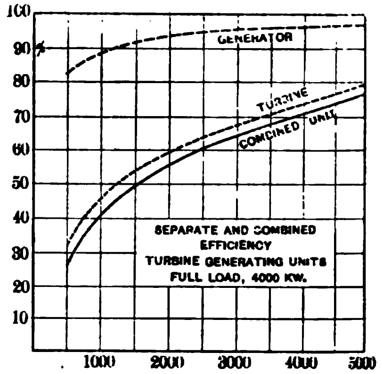


FIG. 2

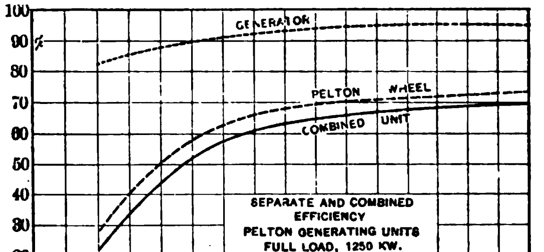


FIG. 3

Losses in the waterwheels and generators were computed from the half-hour wattmeter readings on the generators as recorded in the station report. The input for each output throughout the year was computed from efficiencies shown in tests made in 1909 and checked at the end of 1911. The results show all-day efficiencies for the year as follows:

EFFICIENCY

	Wheel	Generator	Combined
Impulse Unit No. 1	70.8	93.0	65.8
Impulse Unit No. 2	66.3	92.2	61.1
Turbine Unit No. 3	57.1	93.0	53.1
Turbine Unit No. 4	63.6	94.1	59.8
Four units combined	60.7	93.5	56.7

The higher efficiency of the impulse units is due to the fact that they were nearly always loaded above 900 kw. and the regulating was done with the relief valves and governors on the turbines, so that there was little loss from the deflecting nozzles.

The power used in excitation was computed from the half-hour readings on the exciter outputs, and amounted to 399,120 kw-hr. or 1.3 per cent. of the output of the generators. The water input to the exciter units, computed similarly to that of the large units, was 665,200 kw-hr. Station lighting, including light for the employees' cottages, amounted to 175,000 kw-hr. for the year.

Step-Up Transformers. The station is equipped with nine transformers. Each bank of three has a normal capacity of 4500 kw. at 35 deg. cent. temperature rise. These transformers step the voltage from 2,300 to 60,000 volts three-phase star-connected. The neutral of the star connection is grounded. The manufacturers were requested to sacrifice efficiency for high insulation, if necessary, but the efficiency is found to be as high as is customary when using lower insulation. These transformers were all in circuit continuously to keep them in good condition, and their core losses were practically constant, amounting to 926,000 kw-hr., or an average of 11.7 kw. per transformer. The copper loss was computed from the readings on the reports, and

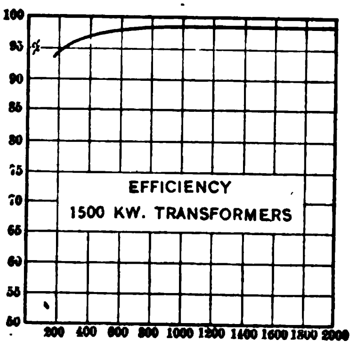


FIG. 4

amounted to 200,00 kw-hr. or an average of 2.54 kw. per transformer.

	Kw-hr.	Average kw.
Core loss	926,000	106
Copper loss	200,000	23
Total loss	1,126,000	129
All-day efficiency	96.1	per cent.

High-Tension Lines. There are two high-tension lines 38.7 miles (62.2 km.) in length strung on two different makes of insulators of practically the same size and type. One of the lines is of No. 2 solid medium hard-drawn copper, the wires being placed in a six-foot (1.83 m.) triangle. The other is built of No. 0000 seven-strand hard-drawn copper, the wires being placed in a seven-foot (2.13 m.) triangle.

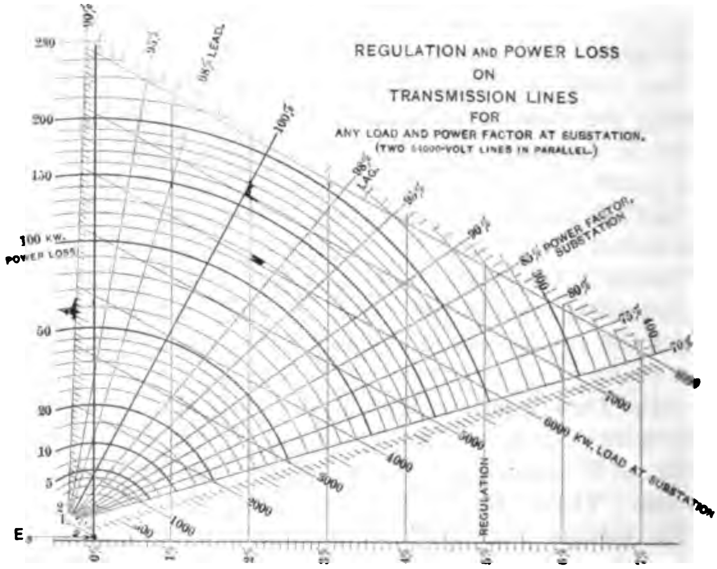


FIG. 5

The line loss was computed from the constants of the lines, taking the load data shown by the report sheets. The line resistances were measured by direct current, using the fall of potential method, and agreed very closely with the computed value. The inductance and capacity were calculated from the values given in the "Standard Handbook," third edition. To simplify calculation for the all-day efficiency, a Perrine-Baum regulation diagram was drawn for both lines in parallel. To this were added circles, taking as a center the end of the substation voltage vector, and as a radius the square of the voltage drop in the line, multiplied by the conductance of the line. The radii of these circles represent power loss. The power lost during 1911 on the two lines, figured from this diagram, using the half-hour readings at the substation for load data, amounted to 378,000 kw-hr. or an average of 43 kw. for the year.

	Kw-hr.	Average kw.
Line loss	378,000	43
All-day efficiency	98.6 per cent.	

Step-Down Transformers. The step-down transformers are placed on the first floor of the substation. There are at present eight of these, each of 1,500 kw. capacity at 35 deg. cent. temperature rise. All are made with a ratio of 54,000 volts, three-phase, to 15,000 and 2,500 Scott-connected two-phase, making four banks of transformers. The low-tension coils are connected in series for 15,000 and in multiple for 2,500 volts, two banks being used on each voltage.

The step-down transformer loss, computed in the same way as that of the step-up transformers, was as follows:

	Kw-hr.	Average kw.
Core loss	692,000	79
Copper loss	217,500	25
Total loss	909,500	104
All-day efficiency	96.6 per cent.	

The sum of the losses in line and transformers was checked against the difference in the watt-hour meter readings on the low-tension side of the transformers at each end of the line, and was about five per cent lower. This may not have been due to error but may be largely due to corona loss or other line leakage. No measurements have as yet been made to determine this point.

Main Substation. The main substation contains the step-down transformers, a distributing switchboard of the remote control type, and the necessary switching and control apparatus for the distributing feeders. The switchboard carries a complete set of curve-tracing meters for the high-tension lines, indicating ammeters and wattmeters and watt-hour meters for the transformers, and indicating ammeters, recording voltmeters and watt-hour meters for the feeders. Loss in meters and their instrument transformers was computed from tests made on each type of meter and transformer. Current used for station light, heat and display lighting was metered.

	Kw-hr.	Average kw.
Loss in meters	29,000	3
Power for station light	317,400	37
Total loss	346,400	40
All-day efficiency	98.7 per cent.	

Motor-Generator Set. A motor-generator set consisting of a 750-h.p., two-phase synchronous motor direct-connected to two 250-kw. 250-volt direct-current compound-wound generators is used on a three-wire 500- and 250-volt system for operating elevators and other motors. The maximum load on this machine at the present time on the direct-current side is 300 kw. and the average load for 1911 was 30.2 kw. The surplus kilovolt-ampere capacity of the motor is utilized in regulating the voltage of the main system by varying the power factor by means of an automatic regulator controlling the field of the motor. There are at present 71 services connected on this system with a connected load of 772½ h.p. The main feeder is 750,000-cir. mil cable with a 400,000-cir. mil neutral, and the branches usually No. 4/0 with No. 2/0 neutral. In all, 27 miles (43.4 km.) of wire are used on this system.

The total loss in the direct-current feeders and the motor-generator was obtained from the difference in the motor watt-hour meters and the customers' meters. From recording voltmeter charts taken at various distributing points and at the substation and from computations, using the load data and line resistance, the line loss is placed at 5 per cent. The details of losses and efficiencies follow:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Motor-generator	38.	417,000	48
Direct-current lines	95.0	12,800	1
Customers' meters	98.8	3,000	..
Total direct-current system	35.7	432,800	49

15,000-*Volt System.* Current is distributed at 15,000 volts from the main substation to two smaller substations and to about twelve mills and factories which use large amounts of power. This system is two-phase, with the center point of each phase grounded. For mechanical reasons, No. 2 is the smallest wire used on the 15,000-volt lines. There are about 105 miles (169 km.) of No. 2, nine miles (14.5 km.) of No. 1, and two and one-half miles (4.02 km.) of No. 0 wire. There are 30 transformers connected, ranging in size from 750 kw. to 50 kw., with a combined capacity of 6,250 kw.

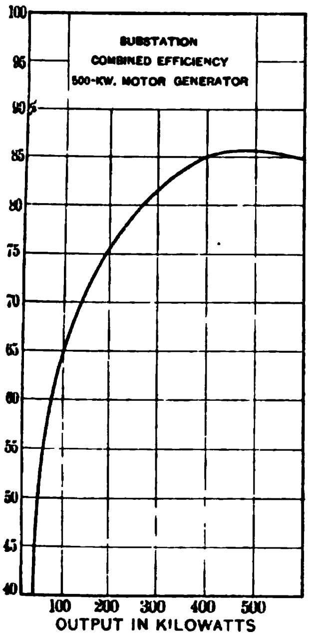


FIG. 6

Loss in the 1,500-volt system was found by taking the difference in the meter readings at substation and at the various receivers, and checked closely by calculation from the line constants and load data. The transformer losses on this system were computed from the load data on the station reports and the tests taken on each size and type of transformer under actual operating conditions.

Copper loss is small compared to core loss because the transformers were lightly loaded; an installation of 6,250 kw. carried an average load of 1,323 kw. The detail losses were:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
15,000-volt lines	99.2	93,500	11
15,000-volt transformers	93.2	775,100	88
Core loss		694,000	79
Copper loss		81,100	9
Total for system	92.5	868,600	99

2,400-*Volt Distributing System.* Power is distributed from the substations by means of seventeen 2,400-volt primary feeders. Of these, twelve are fed from the main substation at Seventh Avenue and Yesler Way, three from Fremont substation and two from West Seattle substation. The more heavily loaded circuits were designed for 200 amperes and the lighter ones for 150 amperes. Number 4/0 wire was used at first, but the economic size for a 200-ampere feeder has been computed at 350,000 cir. mils, which size is now used on the heavier feeders.

An area of 28 square miles (72.5 sq. km.) is served by this system, extending seven miles (11.2 km.) south and six miles (9.6 km.) north of Yesler Way. A distributing point is established at the approximate center of distribution for each feeder and the automatic regulators in this station are set to give the desired voltage at this point.

Connected to the 2,400-volt feeders are 1,082 distributing transformers, ranging in size from 2½ kw. to 50 kw., and with an aggregate full-load capacity of 9,268½ kw. They are connected to give a 240-120-volt three-wire low-tension winding, with the neutral grounded. To aid regulation, a number of transformers of the same size and type are usually connected together on the low-tension side, where conditions will permit. The secondary wire is generally No. 4 for the outside wires and No. 6 for the neutral, with No. 8 for the services. The maximum voltage drop from transformer to customer is kept within 2 volts whenever possible, since there is no way of regulating for voltage between these points. The pressure at the service is kept as near 120 volts as possible. Although standard 2,200-110-volt transformers are used, the pressure has been raised to 2,400 volts, and it is planned to raise it still further to 2,500 volts. This gives about 25 per cent higher core loss, but lowers the copper loss in both transformers and feeders about 29 per cent, and in addition gives nearly 14 per cent better regulation. The 2,400-volt system used 545.4 miles (877.7 km.) of high-tension wire, ranging in size from No. 6 to 350,000 cir. mils, and 1,137.7 miles (1,830.9 km.) of low-tension wire, varying from No. 6 to No. 4/0.

Losses in the feeder regulators were computed from tests made on each type used, in conjunction with load data from the station reports. Losses in distributing transformers were computed in the same way, using also recording ammeter charts taken at distributing points. Losses in the high-tension line were computed from the load data and line resistances of each feeder, and checked by recording voltmeter charts taken at the station and at each distributing point. Loss in low-tension line was estimated from line resistances and load data, and checked by recording voltmeter at the customers' services. Loss in the customers' meters was computed from tests on each type of meter in use.

A check on the various distributing losses is furnished by the difference between the power metered to the customer and that delivered to the distributing system. This amount proved to be slightly greater than the sum of the losses as computed, and the difference was added to the loss in low-tension system, since that loss was most difficult to determine with accuracy. There is also probably a small amount of stolen current included in the low-tension loss. The details of losses on the 2,400-volt commercial system follow:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Feeder regulators	98.6	178,500	20
Primary feeders	96.0	521,600	60
Distributing transformers	88.8	1,391,000	159
Core loss		960,000	110
Copper loss		431,000	49
Secondaries	92.9	782,600	89
Customers' meters	97.6	250,000	29
Total for system	76.2	3,123,700	357

Cluster Light System. The cluster light system comprises 1,631 poles, lighting 25 miles (40.2 km.) of street and carrying 6,851 lamps of a total of 335,700 watts. This system is supplied from 720 kw. in transformers, using 23 miles (37 km.) of primary wire carrying 2,400 volts and 98.4 miles (158.3 km.) of secondary wire in a 240- and 120-volt three-wire system. The voltage is changed from 120 volts to 8 volts in the base of the pole and 8-volt multiple lamps are used. Losses on this system were computed in a similar manner to those on the other distributing systems. They lack the check of integrating meters at the lamp, but were easier to compute on account of the constancy of the load. The transformer losses contain those from the pole-base transformers, which are 250-watt, 8-volt transformers.

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Cluster light primaries	97.0	42,500	5
Cluster light secondaries	93.0	86,500	10
Cluster light transformers	87.8	181,000	21
Core loss	....	117,500	13
Copper loss	....	63,500	7
Total for system	79.1	310,000	35

Series Street Lighting System. The series street light system comprises 683 miles (1,099 km.) of No. 6 wire divided into 29 circuits, lighting 601 miles (967.2 km.) of street. The circuits are connected two in series to 100-light air-cooled constant-current transformers. The voltage on the circuits varies with the number and kind of lamps from 2,500 volts to 5,000 volts. Altogether there are 692 6.6-ampere arc lamps, 5,315 40-c. p. tungsten lamps, and 199 300-c. p. tungsten lamps.

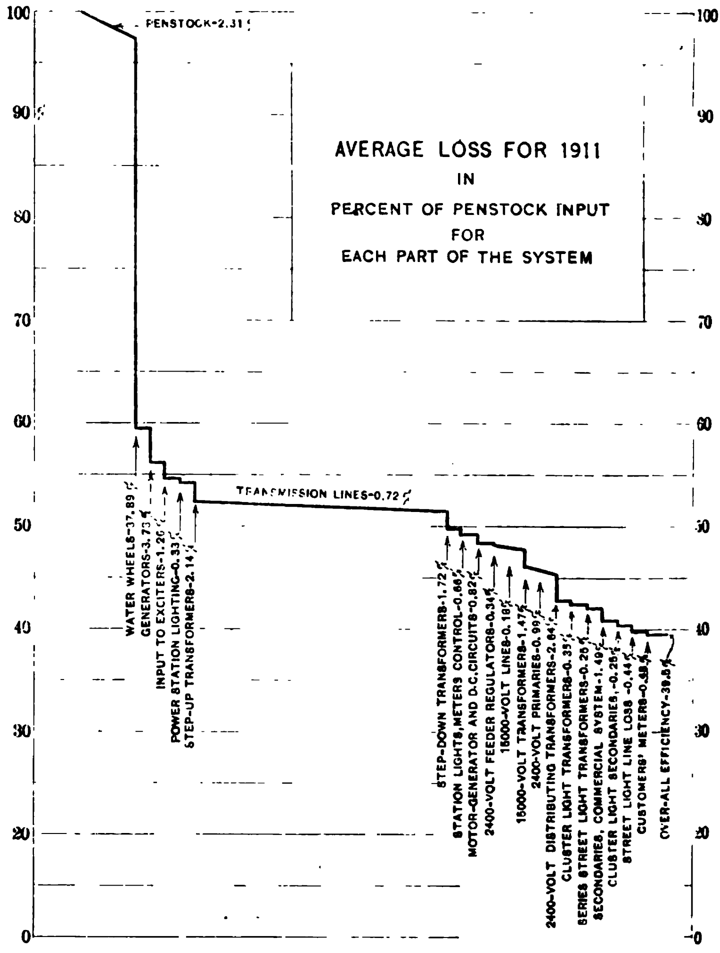


FIG. 7

OUTLINE OF LOSSES AND EFFICIENCIES FOR 1911, SEATTLE MUNICIPAL LIGHT AND POWER PLANT.

	Per cent all-day efficiency	Total 1911 input, kw-hr.	Average 1911 input, kw.	Total 1911 loss, kw-hr.	Average 1911 loss, kw.	Per cent loss	Per cent of penstock input	Per cent of total loss
Generating system	54.4	52,639,000	6009	23,990,300	2739	45.6	45.6	75.3
Penstocks	97.7	52,639,000	6009	1,214,900	139	2.3	2.3	3.8
Generating station	55.7	51,424,100	5870	22,775,400	2600	44.3	43.2	71.5
Water wheels	60.7	50,758,900	5795	19,944,400	2277	39.3	37.9	62.6
Generators	93.5	30,814,500	3518	1,990,800	227	6.5	3.8	6.2
Exciters	....	665,200	76	665,200	76	....	1.3	2.1
Station lights and control	....	175,000	20	175,000	20	....	0.3	0.5
Transmission system	91.6	28,648,700	3270	2,413,500	276	8.4	4.6	7.6
Step up transformers	96.1	28,648,700	3270	1,126,000	129	3.9	2.1	3.5
Transmission lines	98.6	27,522,700	3141	378,000	43	1.4	0.7	1.2
Step-down transformers	96.6	27,144,700	3098	909,500	104	3.4	1.7	2.9
Distributing system	79.2	26,235,200	2994	5,448,700	622	20.8	10.3	17.1
City substation	98.7	26,235,200	2994	346,400	40	1.3	0.7	1.1
S. Lights and control	....	317,400	37	317,400	37	1.2	0.6	1.0
Switchboard meters	....	....	....	29,000	3	....	0.1	0.1
15,000-volt system	92.5	11,587,000	1323	868,600	99	7.5	1.6	2.7
15,000-volt lines	99.2	11,587,000	1323	93,500	11	0.8	0.2	0.3
15,000-volt transformers	93.2	11,493,500	1312	775,100	88	6.8	1.5	2.4
Series street lights	86.3	2,672,800	305	367,200	42	13.7	0.7	1.2
Transformers	95.0	2,672,800	305	133,700	15	5.0	0.3	0.4
Series circuits	90.8	2,539,100	290	233,500	27	9.2	0.4	0.7
Cluster street lights	79.1	1,486,000	170	310,000	35	20.9	0.6	1.0
Cluster transformers	87.8	1,486,000	170	181,000	21	12.2	0.3	0.6
Underground cables	90.1	1,305,000	149	129,000	15	9.9	0.2	0.4
2400-volt commercial system	76.2	13,178,400	1612	3,123,700	357	23.8	5.9	9.8
Feeder regulators	98.6	13,178,400	1612	178,500	20	1.4	0.3	0.6
Primary feeders	96.0	12,999,900	1592	521,600	60	4.0	1.0	1.6
Transformers	88.8	12,478,300	1532	1,391,000	159	11.2	2.6	4.4
Secondaries	92.9	11,087,300	1373	782,600	89	7.1	1.5	2.5
Customers' meters	97.6	10,304,700	1284	250,000	29	2.4	0.5	0.8
Direct-current system	35.7	673,200	77	432,800	49	64.2	0.8	1.4
Motor-generator	38.0	673,200	77	417,000	48	62.0	0.8	1.3
D-C. circuits	95.0	256,200	29	12,800	1	5.0	....	....
Customers' meters	98.8	243,400	28	3,000	....	1.2	....	....

Summary: Total power loss....................31,852,500 kw-hr. Average 3,636 kw.
Total power delivered to customers....................17,304,900 " " 1,975 "
Total power delivered to street lamps....................3,481,600 " " 398 "
Total delivered power....................20,786,500 " " 2,373 "
Over-all efficiency, 39.5 per cent.
[1 kw-hr. at the customers' premises requires 1,364 gallons (5,163 liters) of water from Cedar Lake at average head of 590 feet (179.8m.)].

Losses were computed in a similar manner to those on the cluster light system, and were as follows:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Series lines	90.8	233,500	27
Constant current transformers	95.0	133,700	15
Core loss	....	63,900	7
Copper loss	....	69,800	8
Total for system	86.3	367,200	42

The table on the preceding page shows the losses and efficiencies for each part of the system, and the accompanying diagram shows each loss expressed in per cent of penstock input.

The writer is indebted to Dr. C. E. Magnusson and Professor Harris of the University of Washington for very considerable assistance in tests on pipe lines and generating units, and to Mr. Glen Smith of the City Light Department of Seattle for compilation of tests and data.

The generators and station transformers were also tested by the Electrical Testing Laboratories of New York.

Discussion on "Plant Efficiency—an Analysis of the Losses of a Hydroelectric System" (Ross), Portland, Ore., April 18, 1912.

Gano Dunn: It is startling indeed to see the resulting efficiencies so carefully and accurately computed as they have been in this paper, and it is also startling to see a considerable difference in the amount of this total efficiency from what probably would have been given in the prospectus of a hydroelectric company had the company been in the course of financing instead of in actual operation. In one table there are given certain efficiencies of impulse units and certain turbine units, and both seem considerably low. If I understand Mr. Ross's use of the figures aright, these statistics indicate lower than full load efficiencies. Am I right, Mr. Ross?

J. D. Ross: Yes. The full load efficiencies are given in the curves, Figs. 2 and 3.

Gano Dunn: Of course in a station where there are few units, it is difficult, if not impossible, to run the units at full load. In taking the Institute's honorary member, Dr. C. E. L. Brown, of Switzerland, who rushed through the Pacific Coast a few weeks ago, through the Waterside station of the Edison Company in New York, Mr. Lieb remarked it was one of the strictest rules of the company never to run the machines except at full load, and that, therefore, they never cared what the efficiency of the plant was, and the average load under which the stations had been running in the past was about 101½ per cent. If that is so, why is it not possible to insist in the operation of our systems more upon full load, running units with a view of improving the relatively low efficiency shown by Mr. Ross's calculations. I know the human element is against it, but it needs only for us to be shown what the total diminution is in a case like this, for us to be stimulated, and to do as much as we can to correct it by seeing that the best efficiencies are employed in the apparatus we use. We run a generator or a wheel under a full load, and when the load varies, add units instead of changing the load as a whole. This practise of calculating the accumulation of little quantities is an old but fundamental principle. The differences made by a lot of little things always astonish people that compute them. I think we ought to call Mr. Ross the Benjamin Franklin of the present era because he puts into electrical terms the maxim " Take care of the pennies and the dollars will take care of themselves."

S. J. Lisberger: Mr. Ross has presented to us a valuable paper. I think he has done himself a slight injustice, however, in considering the subject of station lighting or substation lighting as losses to the system. I believe if Mr. Ross had to go before his own board and ask it for more money or possibly an increase in the rate, he would be told he might well justify an increase in rate, or he might justify a demand that he be allowed a certain amount of money for lighting the stations. I don't know how much that will help his losses. I think it has been the rule of most state commissions that the companies are allowed for their own business the actual cost of production of that current as a charge against the particular department in which the current is used. Mr. Ross has stated that the economic size of his alternating feeder is 350,000 cir. mils. That seems at first glance rather an excessive size of copper. As a matter of fact, I don't recall any systems that use that size. I ask him what is the approximate or average distance from the center of distribution to the stations, and at what rate or what value he figures lost current. That will have much to do with the economic size of the feeder in question. I also ask him, in figuring the kilowatt-hour output or kilowatt-hours stolen from the customers' meters, what method he used in making these estimates.

R. Howes: The waterwheel in a hydroelectric plant is at the fountain head, so to speak, as its efficiency affects the entire available output. I would like to ask if there was any specific reason why the turbines should give such a continuously rising efficiency curve. The gates are of a wing type, if I remember correctly, so it would be interesting to know why these wheels were not designed to have maximum efficiency at something less than the full load.

J. B. Fisken: It seems to me that the curves should show the maximum efficiency at about 100 per cent load with a drooping characteristic on either side; the efficiency also seems low. The 100 per cent load shows a turbine efficiency of about 75 per cent. I would like to know whether Mr. Ross can say if that should not be 10 per cent higher. We have no trouble at all in our wheels in getting 86 or 87 per cent and on some of the new wheels we have ordered, we are guaranteed almost ninety per cent. I agree with Mr. Lisberger in regard to the charging of the station lighting. It seems to me that should be charged as an expense and not as a loss, and not against the efficiency of the plant. There might also be a slight saving, I cannot say how much, by the use of three-phase transformers instead of single-phase transformers.

L. F. Harza: I ask Mr. Ross if the 5,000-kw. load is the rated load on the generator. I also ask if a test on the full gate power of the unit was ever made to determine how many kilowatts could be developed. I have found in a number of instances that waterwheels are too large for the generators, and in one instance, a 2500-kw. generator has been operating with waterwheels so large that at the 2500-kw. normal load on the generator, the wheels operate at, as I recall, somewhere about 70 per cent. The wheels are, however, capable of developing better than 80 per cent efficiency, but only at a high overload of the generators, the fault being entirely due to too large capacity of the water wheels rather than inefficiency. The result is that in order to run the unit at normal generator rating, the wheels must operate at low gate opening and hence low efficiency.

There has been a very common trouble in the office where I have been employed in recent years, in buying waterwheels small enough. On one contract we had to reject successively two wheels which were built and tested at Holyoke before we could get the manufacturers to build one of as small a capacity as we wanted. The trouble was, I believe, that we specified that the units must be capable of developing *at least* a certain horse power under a given head, which is a very common specification, and one which we found it necessary to discard on this account. We found that the waterwheel builders design the wheels for a greater capacity in order to meet their power guarantee and apparently cannot predetermine the maximum capacity of their wheels accurately enough to work to that specification without the danger of getting the wheels too large for the generators.

O. B. Coldwell: I have been very much impressed with Mr. Ross's paper, from the short acquaintance I have had with it. I have long been an advocate of attempting to find out what things do in actual practise where they are installed, as against what they might do on the floor of the factory in being tested or at some other point where conditions are not exactly the same as they may be after being installed. Mr. Ross's paper has stated just such an actual condition as that, and I consider it of much more value than a paper dealing merely with the test results not attached to practise. In the company which I represent we have during the past few years been heading in the same direction. We have attempted to test in place, waterwheels, generators, transmission lines and all other parts of the system. To date, we have not put all this together and assembled it as Mr. Ross has been able to do. In the waterwheel tests which we have made, we have employed very largely the Pitot tubes, conditions being such as to make the weir measurements impracticable; at any rate, it would have been a very difficult matter to have used a weir. We have, in addition to water power plants, the steam plants entering into our system as relays, and if we were to attempt to talk about the total efficiency we would have that factor entering in. It so happens that we have two frequencies of generation, 33 cycles, which is the holdover from early practise, and a lot of apparatus of that type, and it is still doing plenty of good work and cannot be dispensed with, and in addition the sixty-cycle; and as we have transmission lines of 33 and 60 cycles working together as a unit more or less, our problem of working out plant efficiency would be more complicated, perhaps. I notice in looking over Mr. Ross's paper that the average losses for the year are the ones shown as the basis of this discussion. I might state that the operating records which we are using in connection with the Portland Railway, Light and Power Company are made up entirely by readings taken from watt-hour meters which are read once every hour. While we have many indicating instruments all over the system, no records are kept of them. The watt-hour meters are read once every hour and plotted on a cross-section sheet by the attendant, with colors used to show the various types of service, and there is thereby on record for the station attendant's benefit, as well as that of the operating department later, an exact picture of what is going on in the station. A number of companies on the coast have load dispatchers' systems and have found them of great advantage. I might say that we are just at the present time installing a system of that sort wherein we will put the question of deciding just how many units are to carry the load, etc., to an expert, rather than leaving it more or less, as it has been done in the past, to the discretion of the operators. Mr. Ross mentions the benefit which may be derived by properly educating the operator in the use of his apparatus. I want to say we have found this particular class of record which we have been keeping—that is, the drawing of a picture, as it were, of the operation of the station from day to day—to be of very great benefit to the operators themselves.

H. Y. Hall: In reference to the point raised by Mr. Dunn as to the operation of units at the most efficient point, I do not think that the operator of the hydroelectric plant is to blame for a unit not being operated at its most efficient point, so far as conditions are in the west, at different hydroelectric plants. Of course, in the case of the New York Edison plant, they have stations with over a dozen units of different sizes and their load is not so very variable, so they can operate at the most efficient point. With a hydroelectric plant the conditions are entirely different. A great many plants are one-unit plants, some two, but very rarely over four units; then the point may be raised as to why put in a lot of units so as to operate some of them at the most efficient point under all load conditions. The question of the load factor comes into consideration, and the cost per unit and the full-load efficiency due to the small units. It seems to me that the criterion isn't so much efficiency. It seems to me that we harp too much on the efficiency and we pay for that efficiency at times when it isn't really worth what we pay. After all, the criterion is what it will cost us, everything considered, to turn out so many kilowatt-hours at such and such load under such and such conditions. With a plant that has no storage capacity the light load efficiencies are not of importance. It is the full load efficiency that is the important point.

J. B. Fisken: I ask Mr. Ross if any Pitot tube measurements were made to check the constants of the weir measurement, and if they were, how many traverses were made with each measurement.

J. D. Ross: In answer to the criticism of Mr. Lisberger that the station lighting losses should not be charged up against the losses of the system, I really believe he is right, for two reasons. One reason is that a good deal of that lighting is for advertising purposes and we are increasing it now on the line of the Milwaukee Railway Company, where we are going to put in a little advertising. I suppose this really should be charged to advertising, the same as printing would be. The station lights inside the building, itself, used for the operators, should be classed a little differently, it is true, but still, perhaps, should be charged up, aside from the losses, as a commercial load. The object of this test, though, was not altogether for the paper; in fact, the test has been going on several years. What we wanted was a full test of our plant. Now, Mr. Hall said that the full-load efficiency was the only thing we can consider in any diversion system. That is practically true. As I said at the outset, this paper is for a storage system, and the distribution end of it is also largely applicable to a steam plant. Where you have a purely diversion system and do not store your water, then, of course, the principal thing is to run your machines at full load. To obtain the maximum efficiency is the important thing. Mr. Hall, also, has stated that too much stress is put on efficiency, and I surely agree with him there. The idea of this test was to raise the efficiency wherever possible, provided this could be done without extra cost, and you will notice there are a lot of little places where that can be done. The question of regulation is very important. You know the man that comes in and kicks usually is not kicking so much on his bill as he is on his regulation, and if there is a lack of efficiency, it can be made up in higher prices a good deal easier than a lack of service can. Of course, where we are, the lack of service sends a man to the other company—some of you are familiar with that, and some not; we always find it is a good thing for the operator, it keeps him alive. I don't believe efficiency is the whole thing by any means. On our secondary, we figure on two volts, maximum, voltage drop; after we get over two volts we try to get busy. Of course, we miss it in a good many cases, but that is our rule.

Mr. Hall has spoken of the rising characteristics of these particular turbines. These turbines were built, the first ones manufactured in this country for a six-hundred-foot head. Now that is a rather delicate question to answer. I never like to answer anything where the manufacturer is concerned, because when we have a difference with a manufacturer, we generally like to settle it with him and after this settlement everything is all right. The makers built an 8600-h.p.wheel. We would like to find a rising curve to full load, and then a falling off, and we have now actually arranged for another pattern of runner. I think, myself, they got the runner a little wrong in the diameter. I am not a waterwheel man. My figures may be entirely wrong. I wouldn't uphold them against those of the designer of a waterwheel, but I think there is a little mistake in the runner, although the wheel is an excellent wheel and the relief valve made by the same people is also doing excellent work.

As to tests, Mr. Fisken, or Mr. Harza, asks if a full load, full gate test has ever been made. At the time the test was made, we ran up to about 5000 kw. on the generator, or about 6600 horse power. In order to get the proper load, we put on rheostats; we took a piece of six-foot stave pipe and put a bottom on it, and placed resistance coils in water in it. We connected the generator to this resistance and took our readings using that load, but the wheel was not up to full gate opening. We also handled that test a good deal as a farmer handles a basket of eggs, for the reason that to follow the test too far might mean a shut-down for the service. We liked the operation and the regulation of these two turbines very well, but at the same time I do believe that a mixture of Peltons and turbines would give a better and quicker response to change of load.

Mr. Coldwell asks whether the Pitot tubes are a success; he says they are attempting to use them and asks if we are trying them. I would like to know Mr. Coldwell's results on the Pitot tube; I would like to see them and compare them with current meter readings, and see the results obtained. We tried the Pitot tube and it may be we did not get the right kind. We made them up, the University tried them, and we tried them, made according to what is considered the best practise, but we failed to have them check with the weir and current meter readings. We took about three-hundred current meter readings in our tail race and also measured the water over the weir. Our load in that test was constant because we put the rheostat on, we kept our power factor constant on the machine and any excess load we carried on another machine. As to the accuracy of the curve, I don't think there is any doubt. We ran complete tests on that curve twice.

We expected about eighty-three per cent efficiency from the turbines, and the contract was so drawn up that any drop in efficiency below that made a forfeiture of a certain amount. The makers were businesslike in the whole thing, and being one of their first machines—the very first one of that head—I think they made a little error in the runner, but we are going to get a new runner with a maximum efficiency at the point we want. I think Mr. Harza asks if 5000 kw. was the normal load of the machine. The guarantee of the manufacturers was 5000 kw. at 40 deg. rise and 4000 kw. at 35 deg., and the machine met the guarantee. Our two Peltons are connected to generators of a different make and they are rated on the same basis of 1500 kw., 40 deg. rise, but we run them right along at 1750 kw.

As to the waterwheels being large in comparison with the generators, I believe that Mr. Harza is right; we ought to have a wheel fitted for the generator it drives. We have merely accepted the wheels subject to the conditions and specifications, which were freely met; and the makers offer to furnish a new runner to give us the efficiency desired at any particular place.

As to the economic size of wire for 200-ampere feeders, 350,000 circular mils may be a little large, but if you take into account voltage regulation, it is better to be above than below the right size, and we believe 350,000 circular mils is about the proper size. For down-town business there is no question about it, because regulation is so important.

*A paper presented at the Pacific Coast Meeting
of the American Institute of Electrical Engineers,
Portland, Ore., April* 18, 1912.

PRACTICAL JOINT POLE CONSTRUCTION

BY J. E. MACDONALD

The object of this paper is to set forth the Los Angeles method of joint pole construction, which five years of practise has proved to be a workable scheme.

Independent operation, accompanied by very rapid development and expansion, had permitted pole conditions to become extremely objectionable to the public as well as to the corporations responsible for them. This reached a critical stage in 1906, when agitation for underground subways for all public utilities marked the beginning of the present cooperative policy. Distribution by the underground method, except in the business district, is impracticable, for the reason that the populated districts demanding service are scattered over a very wide range of territory, there being an entire absence of congestion anywhere.

The problem of joint pole construction was taken up for solution by the principal companies and the result was a general agreement covering the different phases of the work as seemed best fitted for local conditions. These conditions were favorable for the consummation of the project. The old construction stood out boldly as an object lesson in dangerous and unsightly congestion. The undeveloped but rapidly growing districts offered a field for trying the proposition under favorable conditions without any complications. There were some problems in the older districts which were not so readily solved, chief of these being the difficulty of eliminating the capital charges against the existing overhead system of each operating company. It is evident that if any poles are removed before the expiration of their natural life, or if wires are transferred which are providing adequate service, then a certain portion of the original investment must be absorbed in some manner in reconstructing on joint poles. This factor was given proper consideration in the preliminary investigations made in arriving at a satisfactory working agreement. A policy was adopted making the participation in such joint construction entirely optional with each company. However, when any poles are set, it is always with a view to providing space for all parties operating in such location. Even with this liberal policy, there have been but few cases where all companies have not found it to their advantage and profit to join immediately in such construction. Notwithstanding this condition, there has been no unequal division of the financial responsibilities, neither has there been any reason to suspect that the joint work has helped the financing of one project at the expense of another.

The working agreement, which was executed by nine companies operating in common territory, assigned the executive powers to a committee, acting without compensation. This committee is composed of one representative from each member company, all representatives having similar authority regardless of the pole plant owned by the company represented. A secretary, appointed by the committee, is actively in charge of the details of the combination work. An office is maintained independently of the affiliated companies, the expense being prorated uniformly against these member companies. The committee meets monthly for the discussion of combination work, and the consideration of mutual problems. The secretary is advised of all contemplated construction and reconstruction, and plans are made accordingly. to provide for the service of all companies operating in the section where proposed construction or reconstruction is to be undertaken.

The agreement makes certain fundamental stipulations; it defines the general purpose and intention of the agreement; it places certain necessary restrictions on joint work, defining the limits of good practise; it specifies the method of operating under the agreement; the term of agreement and responsibility of each company is predetermined as far as practicable; it limits the manner of occupying and space to be occupied by each party; it fixes valuations and charges, and prescribes regulations governing special expenses and maintenance.

In addition to the foregoing fundamentals, certain general regulations, which should not be considered as arbitrary rulings, have been adopted.

1. *Combined Use of Existing Poles.* In the combination use of existing poles, the combining parties use the highest or most satisfactory poles in the location where it is desired to make combination. The owner of same is permitted to bill the combining parties for a proportional interest at the rate which has been fixed for the valuation of such poles.

2. *Reconstruction by Owning Parties.* When it is desired to reconstruct a pole line in a location where none of the existing poles are suitable for combination use, one of the parties operating in this location sets new poles of standard size and length sufficient for the combination use of all parties operating in this section and for any other party which may desire to obtain space on poles. The constructing or owning party then sells a proportional interest to each party making the combination at the rate which has been fixed for the valuation of such poles. Each party transfers its wires and removes its poles at its own expense.

3. *Reconstruction by New-Coming Party.* When a party is occupying a favorable location on any street or highway, and a second party desires to build a pole line in the same location, if the construction of the first party is entirely satisfactory and adequate for present and future needs, that party is not obligated to assume any expense in connection with the joint occupation of the new pole line built by the second party. The latter builds a pole line suitable for combination use of both parties, and grants and assigns an interest in same to the first party without charge, except that the first party transfers its wires, crossarms and fixtures at its own expense from old poles to new poles. This party removes its poles at its own expense and they remain its individual property. In special cases, however, the second party may be required to pay the entire expense incident to such transfer of wires and removal of poles, and this is determined by the committee, only those participating in the decision who are directly interested in the combination.

4. *New Pole Lines in Undeveloped Territory.* Any party desiring to construct a new pole line in a location where heretofore no pole line has existed, notifies the other members, through the committee, of the proposed construction, and upon request provides space on such poles for the use of all parties who express their intention of combining in their use. The constructing party is then permitted to bill each of the combining parties for a proportional interest at the rate which has been fixed for the valuation of such poles.

5. *Renewing Poles Naturally Decayed.* All poles which have been in use as long as the committee determines that they are safe or satisfactory, or as long as the parties owning shares in same desire to use them, are replaced by new poles. The work of constructing such new pole line is undertaken by one of the parties, as determined by the committee, and this party is permitted to bill the other parties in the same manner as specified heretofore.

6. *Disposition of Joint Property Removed from Service.* Joint poles removed from service may be removed at joint expense to a place designated by the committee, where they may be sold at auction, due notice having been given to each party prior to date of sale. The proceeds of the sale are divided between the owners in proportion to the number of shares owned by each. More frequently it is desirable that such poles should be sold or disposed of before being removed, the purchaser removing same at his own expense. This may be done by mutual agreement or by an exact division of the property in proportion to the shares owned by each party.

7. *Use of Old Poles.* In the combination use of poles, those which have previously been in service elsewhere may be used, and provided that such poles are in other respects equal to new poles, are valued at the same rate as new poles of the same height, except for that portion which has been in the ground, which is considered of no value.

8. *Records.* A record map is prepared for all combinations. Poles are numbered to correspond with house numbers of adjacent property. These maps are supplements to the general agreement and furnish a complete record, specifying the number and size of poles, date when set, valuation, and such other data as may be desirable in each case. These supplements must be approved by all parties interested before any authorization for billing is permitted. A complete file of all combination work is maintained for each company by the committee.

9. *Specifications.* A specification is understood to imply only first class construction, and as a rule, deals with maximum and minimum quantities. Assuming, therefore, that each party is maintaining its lines in the highest state of efficiency, a joint specification is simply a summation of all specifications together with such modifications as are necessary to mutually protect the property of combining parties. This subject is so extensive that it cannot well be covered in a paper of this scope.

The author would refer those seeking enlightenment along this line to the specification adopted by the New York Telephone Company and the Public Service Corporation. This offers an excellent standard of construction, which is worthy of adoption. Local conditions will not demand any radical changes therefrom.

PROGRESS IN LOS ANGELES AND VICINITY

During five years of operation combinations have been recorded on 21,270 poles. By count of poles occupied by two or more parties, it has been determined that the number of those which have been eliminated exceeds 30,000. The length of the average pole in combination use has been found to be 43.04 ft. (13.12 m.)

Figs. 1 and 2 show the conditions at Sixteenth and Georgia Streets before and after reconstruction on joint poles. Sixteenth Street was widened 7.5 ft. (2.3 m.) on each side, and reconstruction was carried on by the utility companies simultaneously with the improvement of the street by the municipality.

Fig. 3 illustrates, in all its crudities, the results of independent operation, three lighting companies and two telephone companies maintaining individual leads on this property line. In the block shown herewith, which is 505 ft. (154 m.) long, there were ten 30-ft. (9.1 m.), nine 35-ft. (10.6 m.) and five 40-ft. (12.2 m.) poles, representing an investment in labor and material for poles of $285.25. The five 40-ft. (12.2 m.) poles, at an investment of $70.00, would have provided better clearances for all companies. Proper construction would demand 50-ft. (15.2 m.) poles in order to comply with a correct specification.

Fig. 4 represents a distributing lead on property line-showing the advantage of joint construction where rights of way are not easily obtained. This is a standard form of construction and easements are usually provided in all new subdivisions for the installation of such construction.

Fig. 5 represents one of a number of square miles (1 sq. mile =2.59 sq. km.) of territory which has been built up during the period that the companies have been operating under the joint agreement. In 1906 this section was traversed by a transmission line and a portion of single track electric railway, on private right of way, which was operated at infrequent intervals for freight traffic only. Other improvements of any kind were lacking. It is now built up with magnificent homes, representing the very best class of residence patronage for the public service corporations. Practically all the lots front east and west, and poles have been placed on north and south property lines for distribution, while the trunk leads have been placed on main streets running east and west, upon which the electric railways have also been constructed. There are 685 combination poles shown on this plot. To accomplish the same distribution by individual construction would have required 1903 poles, that is, provided independent construction would have been tolerated.

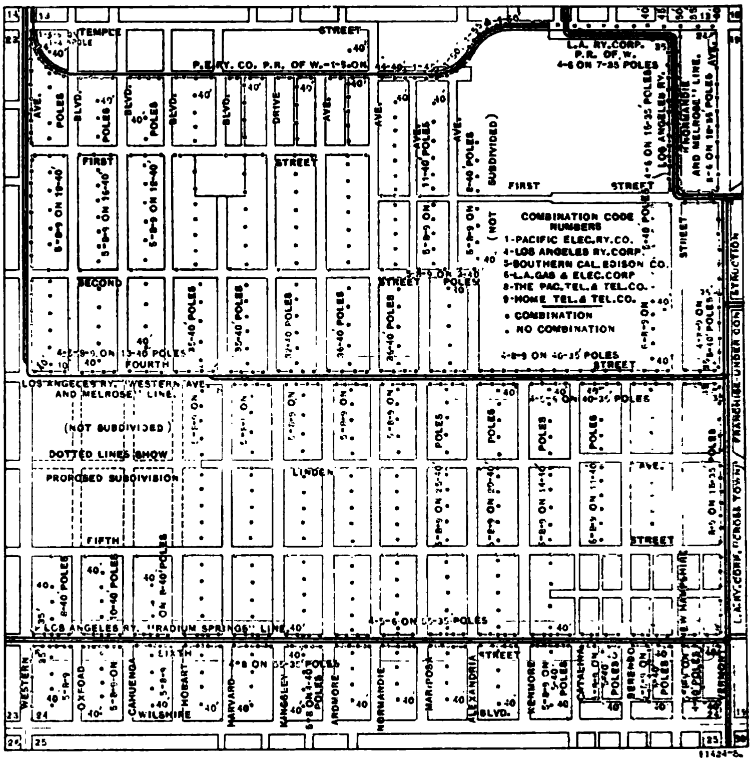


FIG. 5

In the square mile (2.59 sq.km.) there are 193 individually owned poles, which are used almost exclusively for street lighting or railway work. A few of these may ultimately become combination poles. On the south side of Sixth Street will be noted the only duplication in the entire territory. This construction was completed prior to the acceptance of the agreement by the telephone companies, and represents a superfluous pole invest-

PLATE XIII .
A. I. E. E.
VOL. XXXI, 1912

FIG. 1

[MACDONALD]

FIG. 2

[MACDONALD]

FIG. 3 [MACDONALD]

FIG. 4 [MACDONALD]

ment of approximately $614.25. It will, therefore, be noted that failure or neglect to coöperate leads to the possibility of creating objectionable construction, which may be maintained during the entire life of pole line, owing to the expense of transfer.

Figs. 6 to 13, inclusive, show pole conditions on Sunset and Hollywood Boulevards, one of the principal outlets to a suburban community, and represent fairly well the various types of joint construction, where conduit subways would be impracticable from a financial standpoint. These streets form a continuous thoroughfare, extending over seven miles (11.2 km.) in length, from the extreme limit of the present conduit district. Of this there remains less than 3000 ft. (914 m.) which is not improved from the joint construction standpoint.

Fig. 6 shows a combination which is incomplete. The city has underway the work of widening the street and reducing the grade, and joint work is to be completed by the removal of the railway company's poles. The transmission line shown on the north side of the street is the 33,000-volt Edison line built in 1897, this portion now being operated at 15,000 volts. Poles are in fair condition and are not unsuitable for combination use.

Fig. 7 represents joint construction on a curve, where it was impossible to secure permit for anchoring on private property. Poles were trussed at joint expense. There are the municipal fire alarm, two telephone companies, a telegraph company and the railway company operating on one side of the street, and two lighting companies and the railway company on the other. The telegraph company and city are not parties to the general agreement, but cooperate where lines parallel.

Fig. 8 also shows joint construction on a curve; poles on outside of curve have been blocked with concrete at base and at ground line, no guying being necessary. This is a combination of one telegraph company, one telephone company and the railway company on one side of the street, and two lighting companies and the railway company on the other.

Fig. 9 represents a typical straight line combination. Vacant position has been left on top of one line of poles for future installation of transmission line for the railway company. Otherwise, the combination is the same as shown in Fig. 8, except that the view is in the opposite direction.

Figs. 10 and 11 are views taken from the same point looking in opposite directions, one representing a completed combination, and the other a proposition which will be undertaken upon the improvement of the street by the municipality. The railway company owns a private right of way in the center of street and has heretofore maintained center pole construction, this being removed in connection with the combination work.

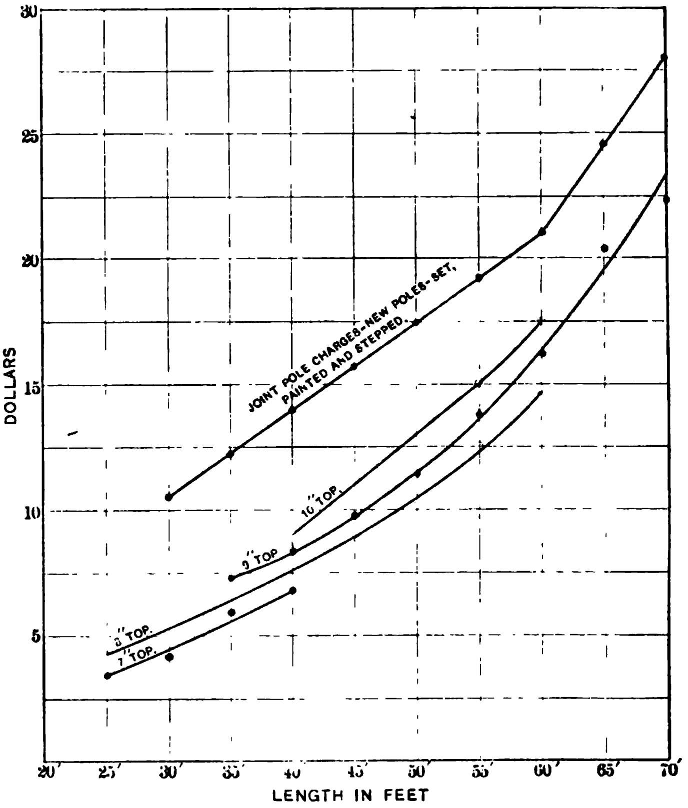


FIG. 14—JOINT POLE VALUES AND MARKET PRICES OF ROUND CEDAR POLES
(Los Angeles, March 1, 1912)

Figs. 12 and 13 illustrate a combination between a railway company and one telephone company, on one side of the street. On the other side is shown the conventional construction of one lighting company and of the railway company.

Fig. 14 is a series of curves showing the present market prices of poles at tidewater points, from which points distribution is

FIG. 6 [MACDONALD]

FIG. 7 [MACDONALD]

FIG. 8 [MACDONALD]

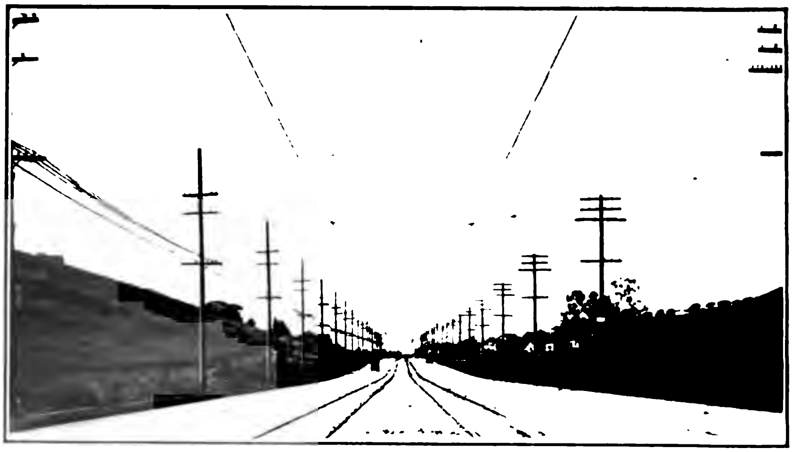


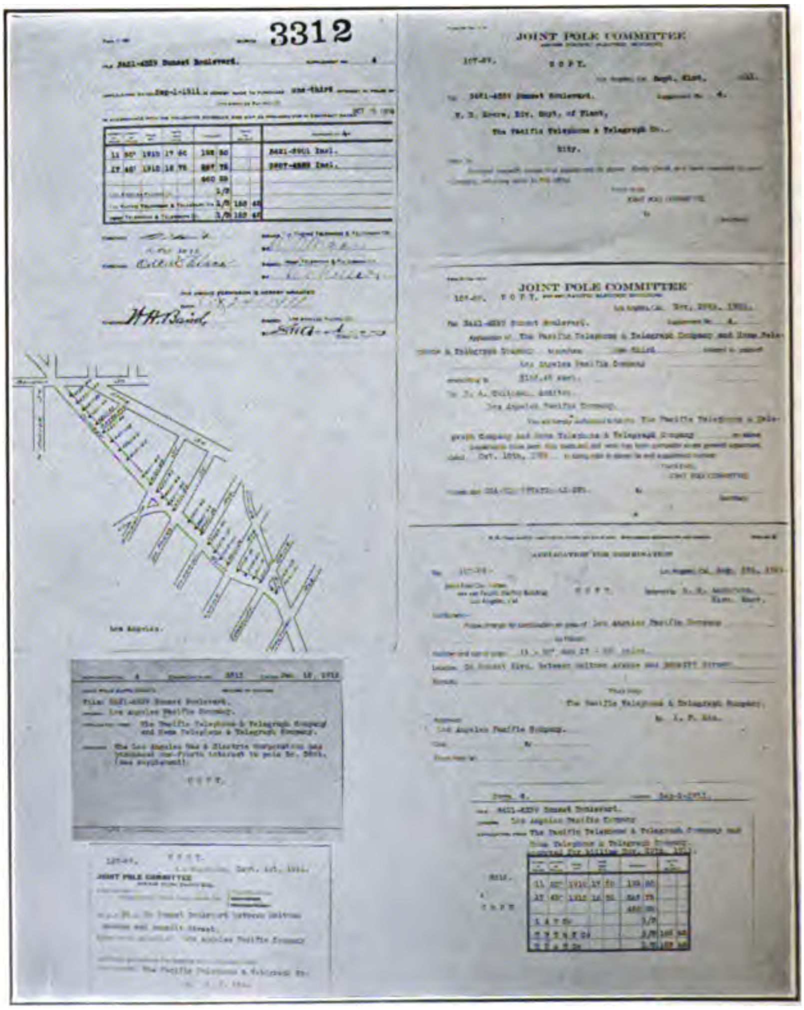
FIG. 9 [MACDONALD]

FIG. 10 [MACDONALD]

FIG. 11 [MACDONALD]

FIG. 12 [MACDONALD]

FIG. 13 [MACDONALD]



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JOINT POLE COMMITTEE

JOINT POLE COMMITTEE

FIG. 15 [MACDONALD]

made locally. Supplementing this, is the curve showing the valuations according to the joint schedule for new poles set, painted and stepped. It will be noted that this gives a valuation of thirty-five cents per pole foot (0.3048 m.) for poles 30 to 60 ft. (9.1 to 18.3 m.) in length. Poles which have been set less than three years are assumed to be of the same value as new poles. Poles set from three to six years are assumed to be of the same value as new poles, but no value is given to that portion of the pole which is in the ground. Poles set over six years are assumed to depreciate at the rate of three and one-half cents per foot per annum, but no value is given to that portion of pole which is in the ground. During five years' operation under this schedule, it has been found that the valuations are approximately correct. The values given for 50-ft. (15.2 m.), 55-ft. (16.7 m.) and 60-ft. (18.3 m.) poles are lower than they should be, but inasmuch as such poles are usually set by the party desiring the top position and the added length is often solely for this party's benefit, it has not been found that the charges prove inequitable.

Fig. 15 shows the practical application of certain forms which have been found useful in maintaining proper records of joint work.

During the five years under discussion no individual, save a newspaper reporter, has precipitated the query " does it pay?" It should not be necessary to furnish exact data on this point. The reduction in investment, that is, the difference between the purchase and installation cost of over 50,000 poles independently owned and operated, as against 21,270 combination poles, is subject to exact deduction. The difference in the maintenance and depreciation charges on them represents a quantity which may also be arrived at very closely. The saving in the maintenance and depreciation charges, at joint expense, of the combination poles for one year exceeds the cost of maintaining the office of the committee for the entire period of five years. In addition to this there are the intangible quantities, such as the saving which results from such a project as a matter of public policy; also the saving due to the entire absence of accidents on joint poles, on account of superior construction. Some of us might even figure on the conservation possibilities, taking the entire United States as a basis of action.

In conclusion it should be stated that whatever degree of success has attended the joint proposition in Los Angeles is due to the constant and consistent policy of cooperation which actuated the engineers of the participating companies. Not a single problem has been presented for solution which has not ultimately been passed upon by unanimous vote. The defection of even one of the nine member companies, so far as participation in joint construction is concerned, could easily have introduced an element of doubt as to the success of the project.

An effort has been made in this brief paper to touch on a few of the problems which will come up for adjudication by those who endeavor to undertake similar projects in joint construction. The suggestions contained herein are the result of five years of development under practically all conditions, and it is hoped that it will be possible for others to inaugurate a system which will solve even better the problem of complete cooperation among utility corporations.

Possibly there are some operating engineers who will find it impossible to secure the cooperation of kindred or opposing interests in such a project. Public opinion is an excellent but uncertain regulator in this respect, and it is to be regretted that some corporations are glad to be publicly coerced into propositions which should have been adopted as sound business policy.

However favorably we feel toward public control, matters of equity, as between the corporations themselves, should be adjusted on an equitable basis without great legal assistance or the compelling influence of a public service commission.

There are few cities in the United States where conditions are favorable for complete underground distribution systems as a possibility of the immediate future. To attempt to accomplish even a small portion of this would be to invite possible financial difficulties. But we can and should make our overhead construction conform to certain limits of decency.

DISCUSSION ON "PRACTICAL JOINT POLE CONSTRUCTION" (MACDONALD), PORTLAND, ORE., APRIL 18, 1912.

A. H. Griswold: I am personally familiar with the proposition which Mr. Macdonald has handled, and I desire to say that it is fully appreciated by the people of Los Angeles, as well as the operating companies.

The Pacific Telephone and Telegraph Company alone, in Los Angeles, owns, either solely or jointly, about 40,000 poles. When you consider that there are nine pole-using companies in Los Angeles, you can realize the relative magnitude of the problem on which Mr. Macdonald has been working.

The joint construction of pole lines provides a wonderful conservation of capital, and it has also done another thing which is of tremendous value. Public agitation on pole lines in connection with the beautifying of streets in the cities and towns is becoming greater every day, and it is only by a proper cooperation of the pole-using companies in constructing joint pole leads that adverse public criticism may be alleviated, and requests for underground construction, which are often prohibitive from a cost standpoint, eliminated.

The slowness of pole-using companies in constructing joint pole lines has provoked so much public agitation that in some states laws are being considered, and recently in one state in the West a law was passed of such an arbitrary nature that to have effected a combination arrangement in accordance with the requirements of that law would have required in some cases 110- or 120-ft. poles. In other words, the requirements were absolutely absurd.

Now if the wire-using companies would cooperate and effect these combinations along good engineering lines, providing for the proper factors of safety, both to life and property, they would forestall much of the agitation, and many of the things that frequently prove oppressive and burdensome to the utility corporations.

I therefore believe that the joint pole question is a very live issue, and as engineers we should consider it very seriously.

There is one point in connection with the joint work that has not been touched upon. There has been no combination made that introduces any physical electrical hazard to any of the other wire-using companies. The low-tension wires, or signal wires, are never placed on the same pole, or the same side of the street, with the high-tension wires of a voltage beyond the limits of the protective devices of the low-tension, or signal circuits. In Los Angeles the high-tension combinations are made on one side of the street on one set of poles, and the low-tension combinations on the other side of the street on another set of poles, and where crossings are necessary, they are effected in an approved manner.

L. B. Cramer: I would like to ask Mr. Macdonald if the telephone companies experience any trouble when their wires are placed on the same pole with lighting companies' primary lighting circuits or arc circuits.

Mr. Macdonald spoke of high-tension wires not being allowed on the same poles with signal wires; at the same time I wondered if the classifications were such as not to be objectionable to the telephone companies from the standpoint of inductive disturbances.

I would also like to ask on what basis the division of shares or units in each pole is made. For example, one company might want space for a 13,000-volt power circuit or a higher voltage power circuit, if such are allowed in the city; another company space for signal wires, telephone circuits, etc. The paper does not cover the division of ownership in each pole.

Gano Dunn: Mr. Macdonald has undoubtedly made out a perfectly conclusive case in favor of joint pole construction as practised in Los Angeles. I am glad Mr. Griswold has contributed to the record certain statements with regard to the hazards, etc., he has just made. I may say the most beautiful pole construction I ever saw was in Los Angeles in this district where Mr. Macdonald and others took me before I came to Portland, so I can fully agree with Mr. Griswold as to the persuasive powers of Mr. Macdonald. As I remember it, Mr. Griswold, in his paper, stated that Los Angeles was in a territory where the weather conditions were very favorable. In other words, Mr. Macdonald has chosen an example of successful joint pole construction where climate and natural conditions most favor it. For the benefit of the TRANSACTIONS of the American Institute of Electrical Engineers, which are spread all over the world, and are certainly read all over the United States critically, I hope Mr. Macdonald, in replying, will give some further information. I hope there will be considerable discussion bearing on the following facts.

In the first place, while there may be no hazards introduced by different types of lines on the same pole, beyond the capacity of the protecting devices to take care of them, yet if the weather conditions were such as to make maintenance of lines themselves much more difficult, then the increased frequency of the operation of those protecting devices and increased interruption to service and other things of that kind, might begin to come in in an economic way, whereas now it does not. In other words, the cost of maintenance of lines and the cost of renewals of protecting devices and the costs, figuring them in cost of interruptions to service, might begin to be, in other districts where the wires are frequently down, a sufficient item of expense to warrant questioning whether or not joint pole construction or possibly underground construction, where there are so many complicated circuits, would not be the proper thing. Then the liability of the relations of the companies should be discussed if we have opportunity. How do the companies share in liability questions, as when a lineman might be operating on one set of wires and be injured on another, or vice versa? What is the actual interference on the circuits and the incidental hazard, and also what is the history of damage of joint pole construction with regard to the injury of employees?

O. B. Coldwell: In Portland we have only to a limited extent tried out this joint pole arrangement. With the telephone companies we have a few arrangements on individual streets and individual lines. In each case we have drawn up with them an agreement covering the matter of liability as well as of construction which should be adopted. It seems to me that the question of liability is one which is of very great importance, and I was rather surprised to hear Mr. Macdonald say there were really nine companies working harmoniously together in Los Angeles. It seems to me the content of his paper is a tribute to the broad-mindedness of the engineers in Los Angeles and their " get together " abilities, not that I have not hopes that equal results might be obtained elsewhere, and that the same thing may be accomplished, but the actual carrying out and putting into practise of such an arrangement is really meritorious. I ask Mr. Macdonald if, in the practical working out of this scheme, each company maintains its own linemen, has access to the poles as it desires for its own wires, going and coming as they please—whether, if that is the case, two or three line gangs arrive at the same pole at the same time, with minor difficulties as a result, or does this Joint Pole Commission have its own crew of linemen for all the companies together? It seems to me the latter would be the only way it could be satisfactorily worked out, and yet, if they are doing it by various crews in Los Angeles, I must be mistaken. I would like to hear from him on that point.

S. J. Lisberger: Does joint pole operation invite a greater hazard than individual pole lines? This is a difficult question to answer. Possibly if all pole lines were built on the same street the hazard would be no greater, perhaps less, with joint poles, due to better pole clearances. But more hazard is introduced because it invites a larger number of wires to be located on the same lead. This is particularly true in territories where competition exists.

The speaker recalls an accident of recent date on a system where a wire of an 11,000-volt lead on the topmost crossarm broke. There was possibly 50,000 h.p. behind the short circuit. It was surprising to see what damage could be done. To those who have never experienced an accident like this it might be interesting to note that the short circuit occurring in this case wiped out the entire pole line for two spans, there being 24 wires on the lead.

Joint pole line construction is advisable where not too many wires are concentrated on a single lead, but where such conditions are likely to occur the speaker deems the problem worthy of careful consideration.

Does the municipality of Los Angeles pay its *pro rata* in the joint pole line construction?

H. R. Wakeman: I would like to ask Mr. Macdonald if the line extensions carried out by the various companies are not somewhat delayed owing to the amount of "red tape" it is necessary to go through in handling them through the joint pole commission. I understand that each time a company wishes to make any line extension it is first necessary for the company to refer the matter to the joint pole commission which thereupon takes the matter up with the other companies before actual construction work commences. This naturally causes some delay and it seems to me it might be one serious disadvantage in working under a joint pole commission.

J. B. Fisken: In regard to the question of liability, it seems to me that the liability to accident is very materially decreased. In our town we have two telephone companies operating, and in some cases one telephone company has come along and strung its wires and cables right through the middle of our lead. We have had arc circuits grounded on its cables, and various troubles. Now the liability to accident does not lie at the point of contact of those wires. Possibly a mile away a telephone lineman may be working on a line which he thinks is dead, but which may at another point be crossed with a high-voltage wire; then he gets hurt. Nothing has been said in regard to the question of cutting trees. I don't know how serious that is in Los Angeles. It is quite a serious proposition with us. We have had a great deal of trouble with the cutting of trees, and this spring we started a crusade on the proposition of tree cutting and I may state we had no assistance from the city government or the park commission. We decided to go to the property owners and ask for permission to trim the trees. So far we have had about three hundred permits this spring, covering about fifteen hundred trees.

We have only had one complaint. One person gave us permission to trim the trees in front of his property. He had two lots, his house being built on one of them and the trees in front of his house were interfering, the others were not. We trimmed the ones in front of the house and then he came in and complained because we didn't trim the others. We have worked along these lines and have had no trouble about trimming trees. I would like to know if Mr. Macdonald's commission has any regular system of getting permission to trim the trees, and if it is assisted by the city government or the park commission or whoever has authority.

We have endeavored in the last few years, as much as possible, to keep off the streets, but unfortunately in Spokane a great many of the finer additions are laid off without any alleys, so we can't go in the alleys. I remember one place where we tried hard to get easements across private property to enable us to build the line there instead of along the street where there was one of our 60,000-volt lines. We could not get it because one property owner held us up. Now does this commission or does any one company have the right of eminent domain? Can they condemn in such cases?

Another thing I would ask is whether easements are taken in the shape of letters, or are they regularly recorded and as such show up in the abstract of title to the property, in other words, are they permanent easements?

On the question of construction, I don't know whether the state of California has a public service commission or not. If it has, does the public service commission allow the expenditure for joint pole construction to be capitalized in cases where lines which are removed are in good order? There is another question which comes very close home to some of us. In the state of Washington there has been a proposition submitted to the public service commission compelling the installation of guard wires above wires which have a limit of 5000 volts maximum where wires of a voltage of over 5000 volts are above them. Of course that applies not only in the towns, but all over the state. It means that if that should pass there would be probably five or six hundred miles of guard wires to be put up and in the cities of course that would be objectionable from the esthetic standpoint, as well as the standpoint of the consequent large expense for maintenance. Is there any such requirement in Los Angeles?

I noted with interest the system of numbering the poles which Mr. Macdonald mentioned in passing. I think he might have dwelt a little longer on that. It happens to be a system we adopted several years ago, after laboring in vain with other systems. The only question I want to ask about that is, where there are poles in an alley, or across private property, is there any definite system in numbering? By that I mean, does the number of any such pole apply to the property east of it, or west of it, or south of it, or north of it?

Nothing was said with reference to the method of hanging large transformers. I don't know what the rules are in Los Angeles, but in putting up transformers we make a dividing line at about five kilowatts, placing small transformers on the regular crossarms and large transformers low down on the pole. In putting up say a 30-kw. transformer on a pole, does that have to be put in the space allotted to the company hanging that transformer or is there provision made to hang it below?

I hope Mr. Macdonald will answer Mr. Griswold's inquiry in regard to handling the gangs working, because at home I can easily picture the situation where one non-union crew would be at work on a pole and a union crew would come along, to go to work on it.

J. E. Macdonald: With reference to the electrical hazard and liability feature of the joint pole proposition, which so many members have mentioned, it should be noted that the practise is to treat such matters exactly as though poles were individually owned. Not one accident has occurred in five years on poles jointly owned in Los Angeles. Even on poles which are not jointly owned, there have been fewer accidents, due to the increased co-operation between the operating companies. All linemen are furnished with printed blanks, of postcard form, with instructions to notify immediately the proper party, by mail, of any defective overhead construction which may be noted. If the defect is serious, they are instructed to use the telephone.

In a number of cases, where failures have occurred on old and obsolete construction, some damage has been recorded, but in these cases it has been possible to determine the responsibility immediately by a prompt inspection of the conditions by the parties interested. This is a much more satisfactory method than that of permitting an indefinite period to elapse, when legal contests have been instituted, as in the old method of permitting the legal departments to be the arbiters in such matters, regardless of existing physical conditions at the time of the accident.

The hazard has seemingly been reduced from purely mechanical reasons. When poles for distribution purposes are erected on both sides of the street or highway, the services of the lighting companies and of the telephone companies cross each other frequently, and in many cases the telephone service is over that of the lighting company. The failure of one service is often accompanied by an interruption of some other service. On the other hand, when the lighting circuits and the telephone circuits are on the same poles on the same side of the street, the services are substantially parallel and the chances for interference are minimized.

The distribution of shares in poles is fixed according to schedule. One share includes any part of:

(a) Space for one, two or three crossarms for regular lighting and power service, or for one or two crossarms for one or two high-tension three-wire transmission circuits, with or without two telephone wires elsewhere on pole.

(b) Span wire attachment or bracket trolley support, with or without crossarm for feeder and telephone.

(c) Space for one, two or three crossarms for telephone service, with or without cable.

Included in one share is space for transformer, lighting fixture, cable terminal or pole platform. This constitutes the maximum allowed for one share, and any company is permitted to purchase additional facilities when necessary.

Although one share includes space for transformer, if it becomes necessary to install one or two large transformers it is the usual practise to encourage the setting of a separate pole for this service. It is not permissible to place a transformer on the same pole with a telephone junction box, neither is it permissible to place a telephone junction box on the same pole with an arc lamp or other lighting fixture.

Before adopting the method of having each party a joint owner in pole or poles used for combination work, some combinations were made on a contract basis at an annual contract charge; also, some were made on a life ownership basis, and others on an annual rental basis. These were found to be not as satisfactory as the present method, where each shareholder has equivalent rights and responsibilities.

In numbering poles on private property, or alleys, it is the usual practise to make reference to the house number on adjoining street.

With reference to specifications, which form a part of the agreement, it has been suggested by Mr. Dunn that the climatic conditions of Southern California are favorable for such an undertaking. This is correct, but it should also be noted that these specifications display but slight modifications from the standard adopted by the National Electric Light Association, which, as stated heretofore, originated with the telephone and power interests of New York and vicinity, where climatic conditions are quite severe. In California, certain modifications have been made necessary largely on account of State regulations.

The maintenance of poles is a joint expense and is pro-rated against each company according to the shares owned by each. This includes repainting, tree trimming and moving when same is necessary. The work is generally undertaken by the original owner of the pole line and proper notice is given to each shareholder of the contemplated work, and, in some cases, an estimate of the cost is submitted, so that there may be no misunderstanding at the time bills are presented for payment.

With a few exceptions, 6600 volts is the maximum operating voltage permitted on poles owned jointly by the power and telephone companies. It is good practise to keep the toll lines of the telephone companies as far removed as practicable from the distributing lines, as well as the transmission lines, of the power companies.

In the matter of tree trimming, the Committee has adopted uniform methods for all companies, it being necessary to secure the permission of the property owner, in writing, in all cases, before applying to the municipality for permit to trim trees. In case the property owner refuses to have trees trimmed, the Board of Public Works may order the work done if it appears necessary, but it is a matter of uncertainty as to whether the municipality has jurisdiction in such cases, and some difficulty has been experienced in securing such permits.

As previously stated, the municipality is not a party to the general agreement. It is to be regretted that certain legal phases of the problem are such as to preclude this possibility at the present time. It has been determined that the municipality has superior rights in streets and public highways and, of itself, this constitutes a serious barrier to such joint construction, although no physical condition exists which is a reason why such construction should not be undertaken in all cases.

The franchises of a number of the Los Angeles operating companies have a provision giving the municipality the right to pole attachments for fire alarm and police signal wires, and similar concessions are accorded the municipality by the other companies in nearly all cases. An unsuccessful effort has recently been made to place this on a business basis at an annual rental of one dollar per pole per year, said rental to include all maintenance charges.

An inquiry has been made as to the attitude of public service commissions toward the companies which are reconstructing on joint poles. On this point, I do not know of any decision which has been rendered covering this feature. There is no doubt, however, that the cost of reconstructing on joint poles is an operating expense and, as such, may not be capitalized.

California has a Railroad Commission, which assumed jurisdiction over all public service corporations on the 23rd of March of this year. The law creating this Commission gives it almost unlimited power, including that of enforcing joint pole construction. In addition to the Railroad Commission, there exists a State statute covering overhead construction. This law was framed largely as a labor measure and does not constitute a correct specification in all respects. One of the features proposed for this law, as first drafted, which fortunately was eliminated, was that of providing guard wires or cradles under high-tension wires at crossings with other circuits. Guard wires have always proved themselves a menace rather than a protection and should, therefore, not be recommended.

It has been suggested that there is a possibility of delay in planning for extensions. This has not been found to be serious. On property line extensions permanent easements are usually provided by the subdivider of the tract. It is current practise to have the realty dealer insert a clause in deeds and contracts, which is worded approximately as follows:

" Subject to a perpetual easement along the rear of said property for the installation and maintenance of poles, crossarms, conduits, wires, cables and other appurtenances for the use of the telephone and electric light companies, with access to same."

In such cases it is possible to estimate far in advance the possibilities and requirements of any given district.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Portland, Ore., April 18, 1912.

AIR GAP FLUX DISTRIBUTION IN DIRECT-CURRENT MACHINES

BY CHARLES R. MOORE

The armature of a direct-current machine under load, reacts on the main field, the effect being commonly known as armature reaction. This reaction always has a tendency to distort the main field and may increase or decrease the total flux per pole, depending on the brush position and the relative values of armature and field strength. The distribution of the flux, then, along the air gap of a direct-current machine is different, when the armature conductors carry current of appreciable strength, from what it is when the machine is running light. The extent of this change in air gap flux distribution determines largely the success of the design, so that it is highly important to be able to determine if possible what the flux distribution will be under load; in fact, no scheme of design can be regarded as complete unless it enables the designer to predetermine with reasonable accuracy the full load as well as the no-load characteristics of a given machine.

As carried out at the present time direct-current machine design points out the no-load characteristics only, the full load characteristics being arrived at by the use of certain constants, applicable to the type and capacity of the machine in question. These constants, being derived from experience, give results sufficiently close for practical cases, but when designs of radical types are attempted the full load characteristics are more or less a matter of conjecture, and the machine must be designed with sufficient liberality to be safe.

The writer believes that this full load condition should be capable of development from fundamental physics rather than from empirical formulas, and the experiments herein described were carried out with this in mind. The general plan of the work has been to study one machine thoroughly rather than to collect an array of data from many machines.

This paper has for its object a description of these experiments, together with a discussion of the method developed by means of which the full load flux distribution of a direct-current machine may be easily and accurately predetermined from design data. The work herein described pertains to generators, but the method is applicable to motors as well.

TESTS

The experimental apparatus consisted in general of a four-pole direct-current machine, having an exploring coil, similar in shape to one of the regular coils, mounted on the armature and connected to two slip rings through which connection could be made to an oscillograph; also such auxiliary apparatus as was necessary to define accurately the conditions obtaining when a film was exposed. The exploring coil had a throw equal to a pole pitch, and was mounted on the surface of the armature by cutting a small groove in one of the retaining wedges and soldering clips to the teeth on either side after the coil was laid in place. The ends of the coil were held down by clips soldered to the binding wires.

It is obvious that, as this coil passed along the air gap at uniform speed, it would have electromotive forces induced in it proportional to the flux cut, and since the spread was inappreciable the curve shown by the oscillograph could be taken as that of flux distribution. In addition to the general shape, the curve secured showed harmonics, giving a notched appearance, as shown in Fig. 9, due to the pulsating reluctance of the magnetic circuit, as the number of teeth under a pole varied from maximum to minimum. This point will be brought out more fully later. The coil used was made up of four turns of No. 24 double cotton-covered magnet wire. The machine on which this coil was mounted was in reality a converter and is shown in Fig 1. This machine was of the type A.C.S., four poles, 7.5 kw. running at 1800 rev. per min. The data under Fig. 1 pertain to this machine.

This machine was one of two similar machines mounted on the same foundation, the two being so arranged that their shafts might be coupled together directly. This afforded an excellent drive as the motor could be run as a synchronous machine giving

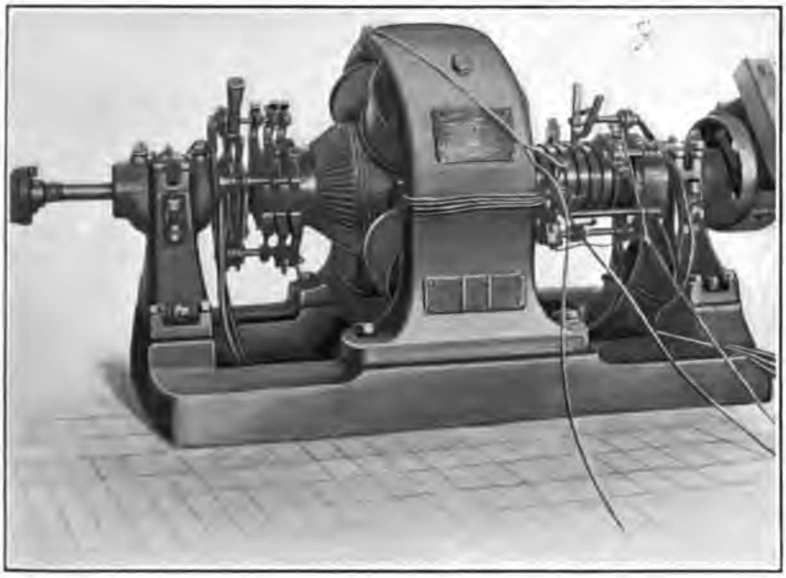

FIG. 1 [MOORE]

MACHINE DATA

Armature Winding:	
Type	Lap
Number of circuits	4
Number of coils	96
Turns per coil	3
Number of armature slots	48
Number of commutator segments	96
Number of armature conductors	576
Field Coils:	
Type	Shunt
Number of turns per coil	1725
Number of coils	4

Length of air gap, ⅛ inch (3.17 mm.).

practically constant speed. In addition to this advantage the synchronous motor on the oscillograph could be run from the same source as the machines being tested, and since this small motor had four poles also, it was in synchronism with the alternating electromotive forces generated in the test coil on the experimental machine. By this arrangement it was unnecessary to take current from the test coil except just enough to operate the oscillograph galvanometer. The tests were run at times when the load on the power station was light or constant so that practically constant speed was assured. A tachometer was used, however, as a check.

As anticipated, the flux distribution curve shifted position along the ground line in the direction of rotation when load was put on the generator, so that, in order to have some reference point whereby this shift could be measured, a contactor was mounted on the shaft and connected in series with a battery and one of the galvanometers of the oscillograph. Once in each revolution of the test machine, this galvanometer threw on the screen a " kick " which was permanent in position regardless of the flux shift. The brush of this contacting device was placed on a rocker arm so that the position of the " kick " could be set at will. The position chosen was the point of zero flux or when the flux curve crossed the ground line at zero load. When load was put on, the shift could be measured directly.

It was also found necessary to have some device for accurately locating the brush position on the films. This requirement was met by placing a second contactor on the shaft close to the commutator and mounting the brush which engaged with it on the rocker-arm to which the regular brushes were attached, so that, as the brushes were shifted, the " kick " shown by the galvanometer to which this contactor was connected moved therewith.

The neutral points on the commutator were located by substituting for one of the regular carbon brushes a wooden brush on the opposite faces of which, in the direction of rotation, were fastened two pieces of strip copper; these bore on the commutator surface, spanning about three segments, and to them was attached a voltmeter. With the machine running light the rocker arm was set with the brushes on the neutral point. The contactor brush was then so adjusted on the stud that the " kick " shown by the galvanometer due to it, coincided with the point where the flux curve crossed the ground line. To set the brushes at the neutral point, with the machine loaded, it was only necessary to shift the rocker arm until the "kick" again coincided with the point of zero flux.

The oscillograph was of the galvanometer type having three cells. After each film was exposed, a calibration line was drawn upon it by impressing on the galvanometer with which the curve was taken a known voltage from battery. Before exposure, the light from all three galvanometers was concentrated on a single spot.

In order to get several curves on a single film, the zero point or point of concentration of the spots of light was moved to one side slightly after each exposure.

Fig. 2 shows the connections used for these tests. The field of the generator as well as that of the oscillograph was excited from a storage battery to insure constant conditions.

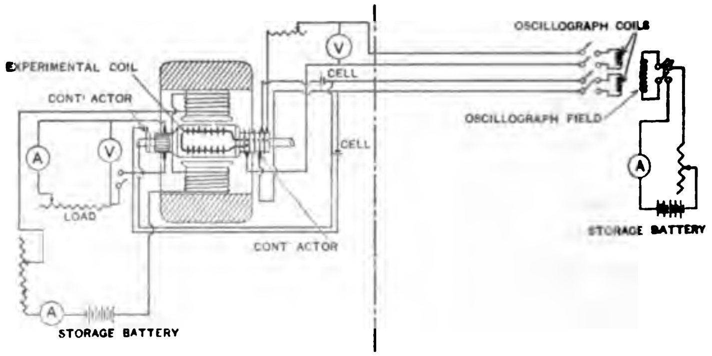

Fig. 2—Diagram of Circuit

Theory

Before discussing data and results it will be necessary to explain the theory followed in working them out.

Professor Goldsborough has read before the Institute* papers dealing with flux distribution in air gaps and armature cores, but nothing has been found in his researches relating to flux distribution in the air gap under load conditions. In the first of his papers he explains the application of the theory of reciprocals, but at that time no oscillograph was available and he found it necessary to check his work by means of commutator exploration. Everyone knows the dangers lurking in the use of

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* See series of papers, Transactions A.I.E.E., 1898, XV, p. 515; 1899, XVI, p. 461, and 1900, XVII, p. 679.

exploring or pilot brushes, so far as quantitative values are concerned, so that it was first necessary to re-check Goldsborough's methods and then to develop a theory applicable to the load condition.

A brief review of Prof. Goldsborough's method as far as we were able to use it will be given. On the pole, as shown in Fig. 3, a series of equally spaced points is laid off and corresponding points are taken on the armature. If the sum of the reciprocals of the distances from any point on the armature to all points on the pole be plotted above the armature point considered, a curve similar to curve A, Fig. 4, will be secured. In the first of his papers above referred to, Prof. Goldsborough gives mathematical methods for calculating the ordinates for this curve, but the writer's experience indicates that so far as time is concerned there is little to be gained in the use of the equations given. Since the pole shoe and armature are symmetrical with respect to the polar axis it is necessary to take armature points on one side only, as shown in Fig. 3. The table of reciprocals is therefore short and the summations may be easily made.

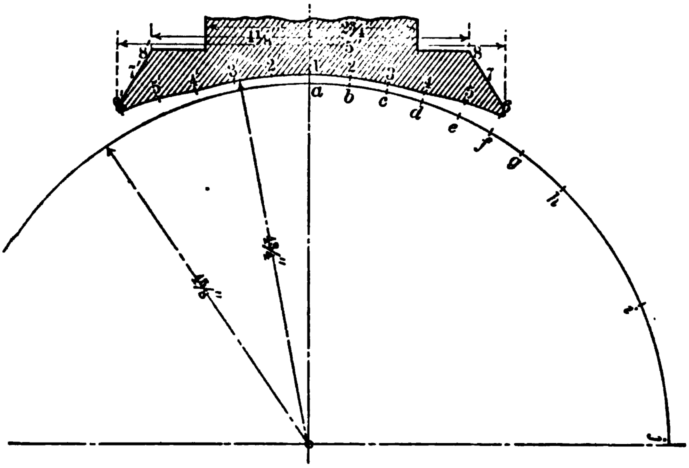


FIG. 3—LAYOUT OF ARMATURE AND POLE FOR OBTAINING THEORETICAL CURVES

Just here it might be remarked that in the finding of curve A, the pole shoe is regarded as an equipotential plane for all points on the pole shoe and the sides of the pole core as of a varying potential for all points that occur beneath the field coil. This automatically takes care of the effect of the field coil itself on flux distribution, for all load conditions. Prof. Goldsborough preferred to call curve *A* a curve of flux distribution when pole *N* was considered as acting alone.

It is obvious that the poles *S* on either side have similar curves but of opposite sign to that of *N* and if these be plotted in their relative positions and added to *A*, algebraically, a curve similar to A_2 results. Prof. Goldsborough, however, considered one pole pitch only, although there seems to be no reason for not considering the entire number of poles a given machine may have. Doing so, however, leads to complication. In Fig. 4 the extremities of curves *A*, etc., are shown for four pole pitches with their algebraic sum A_2.

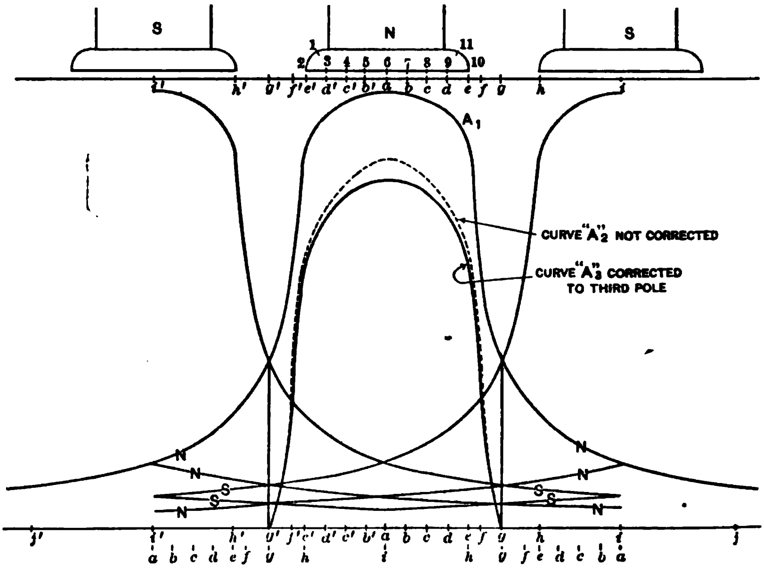


FIG. 4

A better scheme seems to be to consider A_1 as a curve of permeance rather than a curve of flux distribution, since so doing permits one to multiply its ordinates by the values of magnetomotive force acting at the lower extremity, (at the armature points, and these magnetomotive forces may be calculated) thus obtaining a true flux distribution curve.

In order to get a scale for curve *A*, it is necessary to find some point in the air gap where the magnetic lines of force are parallel.

This point is obviously the mid-position along the pole shoe. Knowing the air gap length at this point the reluctance per square centimeter may be calculated, the reciprocal of which may be set equal to the maximum ordinate of the permeance curve and a scale found therefor.

The magnetomotive forces due to the field coils only acting at the various armature points, may be found as follows: Taking the magnetic potential drop along the armature surface between the pole tips as a linear function, (and this assumption is borne out by the tests,) we may represent the magnetomotive forces of two poles relative to the armature as shown in Fig. 5. When no disturbing effects are present on the armature, the magnetomotive force acting on the mid point between the pole tips is zero.

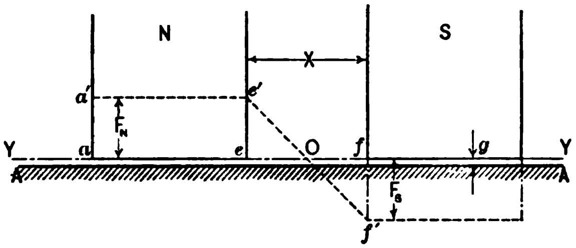


FIG. 5

The magnetic effects of the armature under load may be shown by Fig. 6 as a linear function, having zero value at the middle of the pole shoe and maximum value at a point midway between the poles. Combining these two effects as shown in Fig. 7, the resultant magnetomotive force distribution along the armature surface may be found. Having now the magnetomotive forces acting at the various armature points and the permeance from each point to the pole, it is possible to calculate the flux entering the armature at any given point.

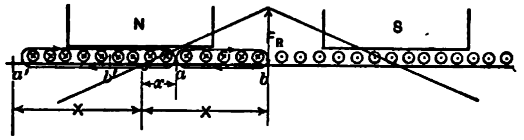


FIG. 6

One other consideration, however, must be taken into account, namely, the reluctance of the teeth, before the real value of flux at a given armature point can be found. This problem, while it may seem complicated at first, may be done without great trouble, as follows:

In Fig. 8 is shown the magnetization curve for the teeth and slots considered as parallel magnetic paths. This curve may be worked out in various ways, but the writer has used in this development a common formula due to Messrs. Parshall and Hobart, which is

$$\mathcal{B}_a = \frac{\mathcal{B}_t\,(w_s + w_t - w_{tf} + w_t \mu f)}{w_t f \mu}$$

where $\mathcal{B}_a$ = apparent density at middle of tooth.
$\mathcal{B}_t$ = actual density at middle of tooth.
W_s = width of slot.
W_t = mean width of tooth.
μ = permeability of tooth at density $\mathcal{B}_t$.
f = per cent of armature length that is iron.

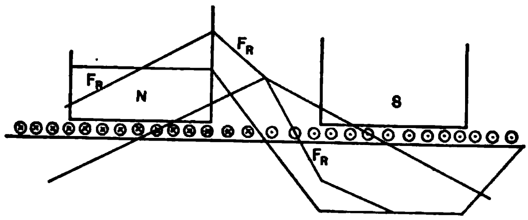


Fig. 7

This formula gives the relation between apparent and actual tooth density so that by assuming various values of $\mathcal{B}_t$ data for a curve may be worked out from which the actual tooth density may be read when the apparent density is known. The necessary ampere-turns for the teeth are then readily calculated.

The straight lines shown in Fig. 8 follow from the value of permeance, for a given armature point, previously explained, the paths being all air paths. Combining now the curve for teeth and slots with the straight lines, a curve of magnetization for each armature point may be found, from which the flux entering that point may be obtained when the magnetomotive force is known. Getting, then, the values of magnetomotive force from the resultant curve as given in Fig. 7, the true values of flux entering all armature points taken may be found.

DATA AND RESULTS

The first effects studied were the shift of field with load, and the effect of field strength on flux position. To this end the curves of Fig. 9 were taken, of which A is the no-load curve, B the full load flux curve but with field excitation the same as for A, and C the full load curve after the field strength had been increased until the total flux per pole was about the same as that shown by curve A. It should be noted that the areas of these curves may be taken as proportional to the total useful flux per pole, so that the decrease in developed voltage as load is thrown on when the field excitation remains constant may be easily studied. Curves given by the oscillograph, however, are usually rather small for quantitative results, but by working carefully a very good idea of the effects present may be secured. It will be noted further that curve A has a notched appearance. That these notches are due to pulsating reluctance of the magnetic circuit may be clearly shown by noting that there are twelve slots per pole and that the frequency of the notches is 24 times that of the fundamental. Furthermore, the notches appear in exactly the same way when the brushes are lifted clear of the commutator and no current whatever is taken from the armature winding.

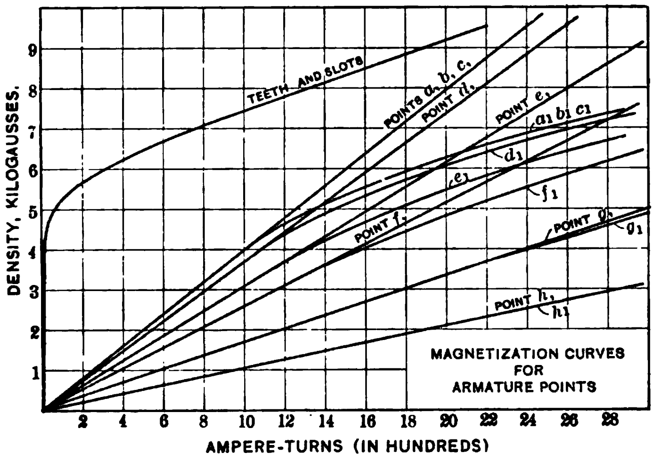


FIG. 8

The extent of the shift can be measured by noting the distance from the contactor deflection to the curve when it crosses the ground line. The ground lines shown in Fig. 9 are not in their true position, and this fact must be taken into account in calculating the shift. Careful measurements taken from Fig. 9 show the flux shift to be about 9.5 per cent of the pole pitch in the direction of rotation.

Curve *C* shifted less than curve *B*, showing that the effect of increasing the field excitation, with a given armature current flowing, is to partially restore the flux curve to its original position. This readjustment comes about from the fact that the reluctance of the teeth under the trailing pole tip increases with flux density faster than the reluctance of those under the leading tip.

The effort made to get the areas of test curves *A* and *C* the same, was not altogether successful, owing to the fact that it was necessary to measure the value of the field flux by connecting a voltmeter across the slip rings to which the exploring coil was attached. It is obvious that the effective values of voltage, which are proportional to the r.m.s. of the flux curves, are not the same for equal areas on account of changes in shape of the flux curves. The areas secured, however, were sufficiently accurate for the purpose.

The effect of commutation and brush position on the main field was next studied and is shown in Fig. 10. So long as the brushes remain practically at the neutral point and do not short-circuit turns in a field of very great strength the effect on the main field is slight. However, as the brushes are moved to positions where the short-circuited turns are in a dense field the short-circuit currents rise to values that do affect considerably the main field strength. In Fig. 10, the curves are designated the same as in Fig. 9. It will be noted that as the exploring coil passes the brush position, *i.e.*, the coil in the slot beneath it undergoes commutation, the effect of the short-circuit flux is clearly shown by the increased height of the points. The writer is at present making an experimental study of reactance voltage of the commutated coil, using as a basis the difference in height of the points as illustrated.

It was very interesting to watch the movement of the notches as the brushes were shifted from the neutral position. At the exact neutral these notches or points were about the same in height when the armature was loaded as when running light. However, the magnitude of the short-circuited current increased with change in brush position regardless of the direction of shift,

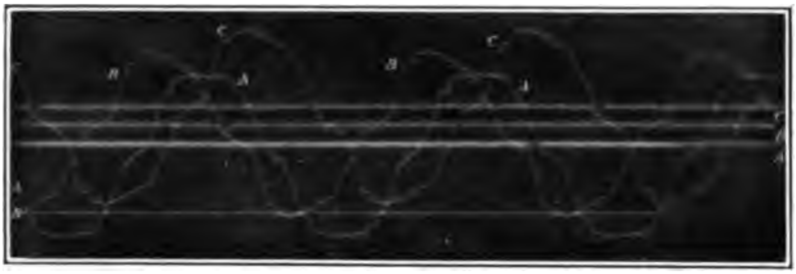


FIG. 9 [MOORE]

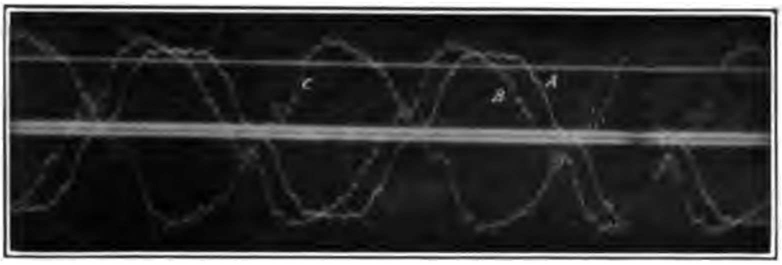


FIG. 10 [MOORE]

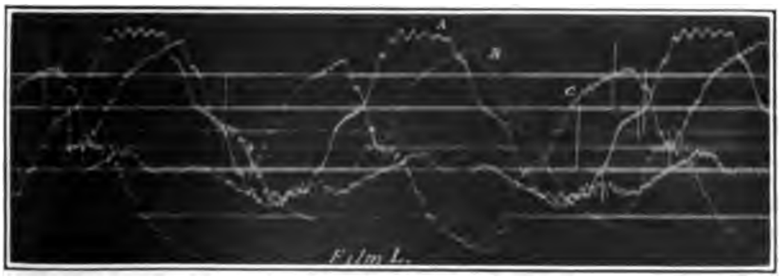


FIG. 14 [MOORE]

and since the coil was in the best position for action on the field, the height of the notches increased. As the pulsations due to varying reluctance coincided with the effects of the short-circuited coil the notches increased greatly in height. When these actions were opposed, the notches were very much reduced. The frequency with which a commutator bar left a brush was just double the frequency of the pulsations of reluctance, and the combined effect is clearly shown on some of the films by a large and small notch alternately placed. By neutral point is meant the real position of zero magnetomotive force on the armature and not the no-load neutral. This is explained more fully in the appendix.

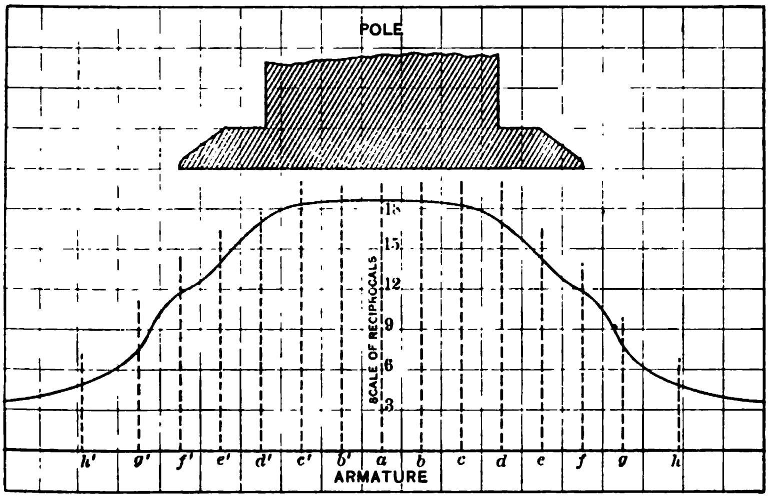


Fig. 11

The most important considerations with which this investigation has to deal, pertain to the shape of the flux curves and the derivation of a scale therefor. In comparing calculated with experimental curves, relative to shape, the areas and pitches were made equal, so that a common value of total flux was represented by them. Fig. 11 shows the permeance curve for one pole of the test machine. This curve was derived by the method of reciprocals, the points on the pole shoe and armature surfaces being laid off as shown in Fig. 3.

Having the permeance curve, which has to do with the ability of a given magnetomotive force to send flux from any armature point to the pole as a whole, or vice versa, and the magnetization curve for the teeth and slots, magnetization curves may be derived for all armature points. In Fig. 8, the straight lines show the relation between density and ampere-turns for the various armature points, so far as the air path only is concerned. The slopes of these lines marked *a*, *b*, *c*, were determined by the air gap length at the middle of the pole face. The slopes of the other straight lines were determined by taking the slope of the first line as equal to the maximum value of the permeance curve and calculating a scale by means of which the direction of the lines corresponding to the various armature points could be calculated.

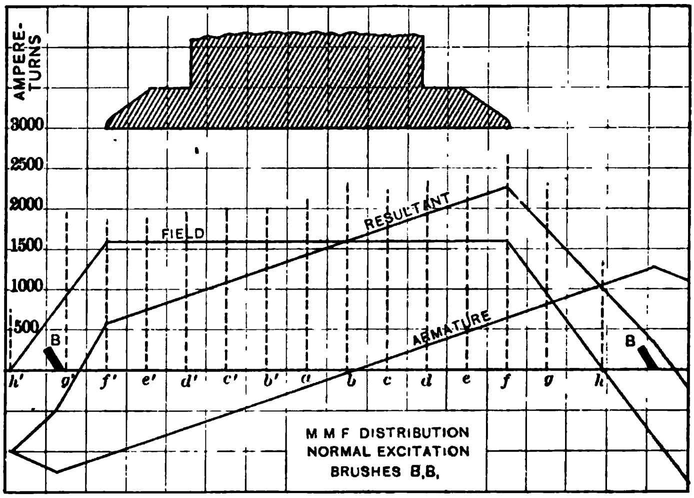


FIG. 12

By combining the teeth and slots curve with these straight lines the real magnetization curves for all armature points could be found. These resultant curves are also shown in Fig. 8.

Fig. 12 shows the distribution of the pole and armature magnetomotive forces under normal excitation and load, together with their resultant. By taking values of magnetomotive forces for the various armature points, using the field magnetomotive force distribution curve only, and reading the corresponding densities from the proper curves in Fig. 8, the no-load flux distribution curve results as shown by curve *C* in Fig. 13. By choosing magnetomotive force values from the resultant magnetomotive force curve in Fig. 12, and again reading the densities from the proper magnetization curves in Fig. 8, curve C_1, Fig. 13, results, which is the full-load flux distribution curve, the field excitation remaining constant. The dotted curves in Fig. 13 represent the actual flux distribution along the armature surface for the no-load and full-load condition.

These curves agree so closely that in order to be sure of the method, similar curves were worked out for low excitations, and correspondingly low armature load. To this end the curves of Fig. 14 were taken, the field excitation being slightly less than 300 ampere-turns per pole. For the sake of clearness these curves have been traced as shown in Fig. 15 and the ground lines put in their proper positions.

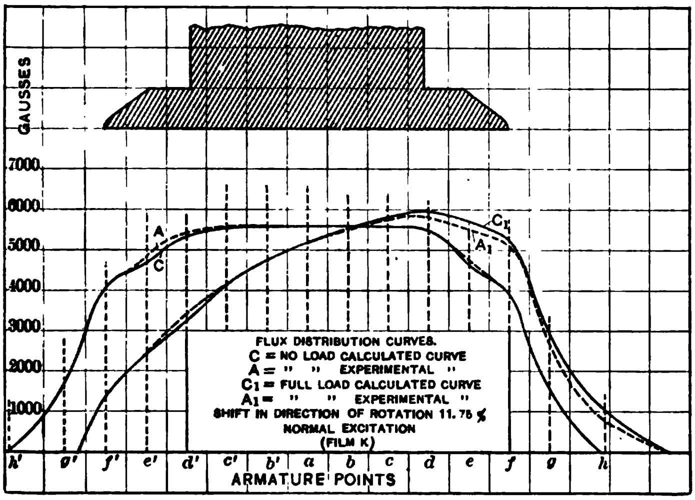


FIG. 13

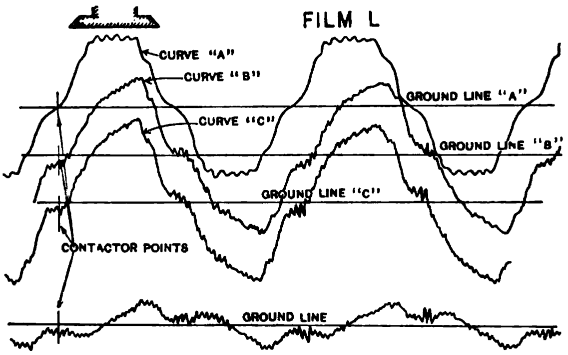
Fig. 16 shows the armature and field magnetomotive force distribution and Fig. 17 shows the no-load and full-load flux distribution curves. It will be noted that the experimental curves follow the calculated curves about as closely as is the case in Fig. 13, showing that the method takes into account properly the effect of tooth reluctance.

It should be further pointed out that the maximum flux density in the case of normal excitation, Fig. 13, does not rise much above the no-load maximum values, showing that the teeth are well saturated. With low excitation this difference is greater.

The notches in the actual flux curves have been omitted for the sake of clearness since they in no way affect the general shape.

At the bottom of Fig. 15, is shown a curve of flux distribution caused by the armature current acting alone, *i.e.*, the field current zero and the armature currents forced through by an external voltage. Since this curve has little practical value no attempt was made to derive a calculated curve to check it.

As previously pointed out, the areas of the curves *A*, *B* and *C* are proportional to the developed voltages, so that in a given design the drop in voltage, due to reduction of flux caused by armature reaction, may be found and compensated for by adding sufficient excitation to the field to bring the area of curve *C* up to that value which indicates sufficient flux to overcome the armature and brush resistance drop, plus the developed voltage at no-load. This may be done by finding first the average air gap densities as given by curves *A* and *B*, and noting the values of field ampere-turns given by them on the magnetization curve for the air gap, teeth and slots. This difference is the number of ampere-turns per pole equivalent to armature reaction and this value must be added directly to the field excitation to compensate for armature effects. The armature and brush resistance drops may be computed and added to the no-load voltage and an average air gap flux density calculated to give the full-load developed voltage. The ampere-turns necessary to produce this increase may be found in the ordinary manner.



FLUX DISTRIBUTION: FIELD CURRENT ZERO ARMATURE CURRENT 12 AMPERES

FIG. 15

With the full-load field excitation thus determined, curve *C* may be worked out, which will be the true flux distribution curve along the armature surface when the machine is fully loaded and all the effects producing internal loss of voltage are compensated for.

One of the points of interest to the student and engineer, resulting from having the load flux distribution curves, relates to brush position. Having the inductance of the commutated coil, Dr. Steinmetz, in his "Elements of Electrical Engineering," has already pointed out methods for calculating the proper density in which the coil should move in order exactly to reverse the current, so that by locating this value on the curve near the leading pole tip the brush position may be determined.

It is obvious that since the brush position affects somewhat the shape of the load curves, the position just found will be slightly in error, but experiment shows that for a reasonable shift of the brush position the areas under the load curves are not materially altered. In cases where the brush shift must be excessive it is a simple matter to derive a second full-load curve taking into account the new brush position.

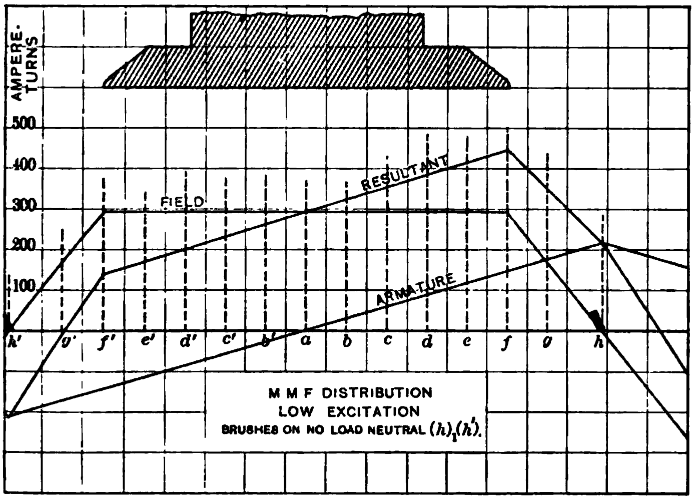


Fig. 16

Conclusion

The conclusions to be derived from the above are:

a. The flux distribution curves for any load may be obtained with an accuracy closely approaching experimental observations.

b. The positions of these flux curves are affected but little by brush position when the brush remains near the neutral point.

c. Field ampere-turns needed for overcoming the armature reactions may be calculated without any special reference to cross magnetization or demagnetization in the sense given in standard texts.

d. The brush position may be found accurately from design data.

APPENDIX

In the course of these experiments and studies several points of interest not pertaining to the final result came up. The first of these relates to the getting of a $\mathcal{B}$-H curve for the armature iron of the test machine. The manufacturers were unable to supply an accurate curve for this machine. Furthermore, it was impossible to separate from the magnetization curve of the entire magnetic circuit, that part having to do with the armature iron only. Fortunately, however, the armature was constructed with two air ducts equally spaced, so that by sending a large current through the shaft and threading a coil which was connected to a ballistic galvanometer through the air ducts and around the middle section of the armature iron a satisfactory $\mathcal{B}$-H curve was secured.

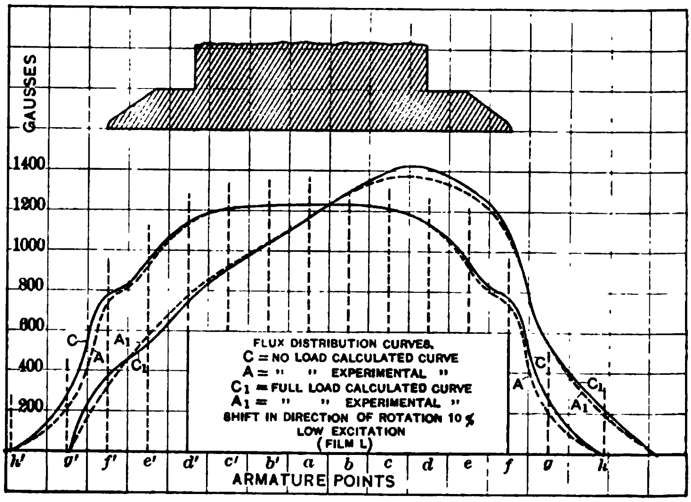


FIG. 17

The second point had to do with the methods ordinarily given for calculating the demagnetizing ampere-turns of an armature. As ordinarily taken, these ampere-turns occupy the space designated by the double angle between the brush position and the no-load neutral. These experiments, however, show that as the load comes on the armature, the real neutral shifts in the direction of rotation, the effect being exactly the same as if the poles themselves were rotated, relative to the brushes, a like amount. Furthermore, the position of the flux curve is affected very little by brush position, so that it is erroneous to measure to the no-load neutral in the calculation of the demagnetizing ampere-turns. Obviously the true point for load conditions can only be found by developing the flux distribution curve and, when this is done by the methods herein given, the element of cross-magnetization and demagnetization vanishes from the calculations, the extra ampere-turns needed for overcoming the armature effects being found directly after the area of curve *B* is obtained and compared with curve *A*.

The experiments show that the effect of the so-called cross-magnetizing ampere-turns is much larger for a given case than has usually been charged against them, and that the effect of the demagnetizing ampere-turns is much smaller than the values given by the usual methods of calculation.

In closing, the writer wishes to express his sincere appreciation for the untiring efforts of Messrs. R. E. Pumphrey, C. S. Beardsley, H. Kessel and J. B. Sheadel, members of the class of 1911, School of Electrical Engineering, Purdue University. These men assisted the writer in the performance of the tests above described and used the experiments as a basis for their undergraduate theses.

Discussion on “Air Gap Flux Distribution in Direct-Current Machines” (Moore), Portland, Ore., April 18, 1912.

H. Weichsel: The method used by Mr. Moore for investigating the actual flux distribution in a direct-current machine consists in determining by means of an oscillograph the wave shape of the alternating e.m.f. generated in an armature coil spanning 180 electrical degrees. The assumption is then made that the field distribution is similar to the wave shape of the generated e.m.f., provided we consider that the base line of the half wave is equal to the pole pitch of the machine. This assumption leads to correct results if the field distribution is absolutely constant and does not change with time. If, however, the field distribution or the field strength changes with time this method must lead to incorrect results.

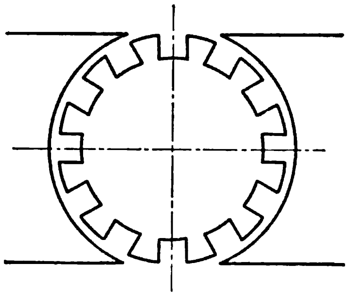


Fig. 1

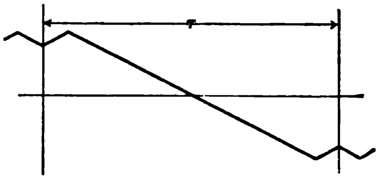


Fig. 4

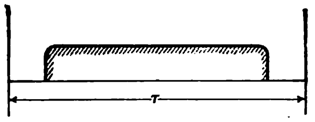


Fig. 3

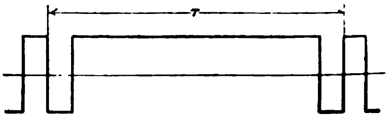


Fig. 5

In a direct-current machine with an unslotted armature it is true that the field distribution is independent of time, and the above method will give correct results. If, however, the armature is slotted it is evident that the field distribution changes with time because the teeth have a tendency to drag the flux in the direction of rotation.

In Fig. 1 a two-pole machine with 12 armature slots is shown and in the following discussion we will assume that the machine has no fringing. The field distribution over the armature surface at the moment that a slot center coincides with the center line of the pole may be represented by Fig. 2*a*. Likewise Fig 2*b*, 2*c*, etc., represent the field distribution over the armature surface after the armature has moved a distance equal to

$p/8$, $2p/8$, etc., where p equals the tooth pitch. The average field strength for a certain point on the armature circumference can therefore be obtained by finding the average of all the above ordinates for the point under consideration. By computing this for a series of points the average field distribution in space over the whole armature surface has been obtained as shown in Fig. 3.

Mr. Moore makes the assumption that the wave shape of the e.m.f. coincides with this field distribution.

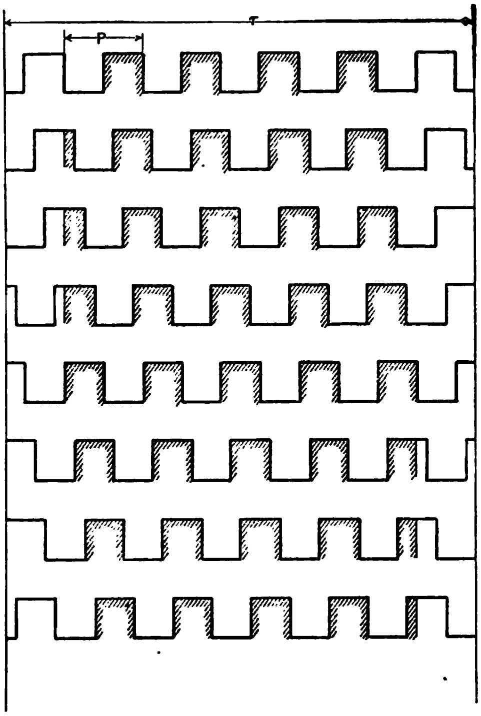


FIG. 2

It is an easy matter to predetermine the wave shape of the e.m.f. by the fundamental induction law

$$E = \frac{dN}{dt} . s$$

where N represents the lines penetrating the coil with s turns. Therefore if we plot a curve with the total lines penetrating the search coil as a function of time (assuming constant velocity of armature) we can obtain the e.m.f. generated at any given instant by drawing the tangent to the curve at that point. Fig. 4 shows the total lines interlinked with the search coil plotted as a function of time, as found by the use of Fig. 2. Fig. 5 is the e.m.f. curve obtained by plotting the values of the tangents to the curve shown in Fig. 4. A comparison of Fig. 5 and Fig. 3 shows at a glance that these two curves are entirely different. The assumption that the wave shape of the generated e.m.f. represents the average field distribution on the armature is therefore not correct for the case in which the armature field changes its shape with time.

The conclusions drawn in Mr. Moore's paper will, however, be correct in general, because, owing to the fringing of the lines, the field does not change very materially with time; but I believe great care must be exercised in trying to analyze the meaning of small ripples in the oscillogram as has been attempted in Mr. Moore's paper.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 25, 1912.

SELF-STARTING SYNCHRONOUS MOTORS

BY CARL J. FECHHEIMER

The following treatment of the starting of synchronous motors is intended to apply to polyphase motors and has been worked out for those of the revolving field type, but can doubtless be so modified as to apply to motors of the revolving armature type as well. The analytical treatment of the subject applies to motors with definite pole construction. The writer has not investigated in any way the starting of motors of the round rotor type, such as are used in the construction of large high-speed turbo-generators.

In polyphase induction motors the starting torque is proportional to the product of the current in phase with the flux multiplied by the flux. The simplest example of this is a two-phase motor in which the torque is produced by the flux arising from the magnetomotive force of phase one, multiplied by the component of current in phase two which is in time-phase with the flux. As the flux is in time quadrature with the impressed electromotive force of phase one, and the conductors in phase two lie in this flux, it will be seen that the component of current in phase two which is productive of torque is the component which is in time-phase with its impressed electromotive force; in other words, the starting torque is proportional to the power input to the rotor. As has often been demonstrated with induction motors, the starting torque expressed in synchronous watts is equal to the power input to the rotor expressed in true watts.

The same principle can be shown to apply in a similar way to three-phase machines; but the truth of this has been so well established and realized by all who have designed induction motors, that the validity thereof can, without further proof, be well appreciated by those who are familiar with the phenomenon referred to.

When a polyphase electromotive force is applied to the stator of a synchronous motor it produces a rotating field in the same manner as is the case with an induction motor. If the rotor be stationary, electromotive forces are induced therein, which in turn cause currents to flow, the values of which depend upon the electromotive forces and the impedances of their paths.

If the entire rotor structure be well laminated, these currents are so small in magnitude that they will have little reaction upon the flux which produces them. On the other hand, if the poles only are laminated, and the field ring made solid, of steel or cast iron, the currents will then be in the form of eddies in the solid structure. These currents, being induced by transformer action between the stator and the rotor, must react upon the stator and cause currents to flow in the stator conductors which have magnetomotive forces equal and opposite to those which flow in the rotor. If the characteristics of the solid rotor were such as to cause the eddy currents induced therein to lag 90 degrees behind the electromotive forces which produce them, then it will be seen that the stator currents, the magnetomotive forces of which are opposed to those in the rotor, are also in time quadrature with the stator equivalent of electromotive forces induced in the rotor. In this case, the conception of the manner of production of torque is that the in-phase components of the currents in the stator conductors, the magnetomotive forces of which neutralize the in-phase currents in the rotor, act with the flux to produce forces at the periphery. As the stator is secured in position, the rotor starts to revolve.

It is only a small step from this to the case of the synchronous motor with a solid field ring, laminated poles and squirrel cage or amortisseur winding; that is, the starting torque is proportional to the components of the currents in the rotor circuit which are in phase with the electromotive forces that produce them, regardless of whether the currents are in the field ring, in the amortisseur winding, in the rivets which hold the poles together, or in the collars around the poles. If we have a laminated rotor body, we confine nearly all the in-phase currents to the amortisseur winding and collars around the heads of the poles, if such are used. In this latter case we may regard the torque as being produced by the components of the currents in the rotor bars which are in phase with the flux.

It will also be readily seen that were the rotor to have solid poles instead of laminated, the same general principles would apply. Due to the large reaction of the eddies which are induced in the solid pole shoes in this latter case, the flux does not penetrate into the pole body to nearly so great an extent as is the case with laminated poles; that is, the eddy currents which are induced in the poles tend to keep the flux from entering them, producing the well-known skin-effect phenomenon.

In starting a synchronous motor by applying voltage to the stator, the same conditions obtain as in the induction motor. In other words, to secure any starting torque, it is essential to have currents in the rotor lagging less than 90 degrees behind the electromotive forces which produce them.

Upon the foregoing principle are based all of the calculations and derivations of formulas in this paper; that is, we have only to determine the power input to the rotor and we at once obtain the starting torque. In order to verify this, a number of experiments have been conducted on machines with laminated poles, cast steel field rings, with and without amortisseur windings; and also on machines with solid poles, solid field rings and solid pole shoes. The torque was measured by means of a brake, and due allowance was made for discrepancies caused by the static friction of the bearings.

The power input to the stator was measured by means of wattmeters, the current was measured by ammeters in all phases, and the electromotive forces measured across all phases. The power input to the rotor was determined by deducting the stator copper loss from the stator input. In comparison with the stator copper loss, the core loss was so small that it could be neglected. There were, to be sure, certain points of difference, in some cases the starting torque being slightly greater than obtained by deducting the loss in the stator from the power input, and while in other cases it was slightly less, the discrepancy in general was about the same as is obtained when making starting torque tests on induction motors. For further discussion of this point, see " Non-Uniformity of Torque at the Instant of Starting," " Unbalance in Phases," and " Star and Delta Connection," treated in subsequent sections of this paper.

One apparent source of error, which cannot be neglected, was the marked effect of variation in starting torque with different positions of the rotor. It was found, however, in general, that the average starting torque agreed very well with the power input to the stator minus the losses in the stator.

From the above it will be seen that in order to secure large starting torque with small currents from the line, it is essential:

1. To make the losses in the rotor high by using relatively large resistances.

2. To minimize the reactance due to leakage fields which interlink with currents induced in the conductors in the rotor at the instant of starting.

3. To reduce as much as possible the reactance due to leakage fields in the stator, as these greatly increase the electromotive force which it is necessary to impress upon the stator.

4. To make the magnetomotive force required to drive the flux across the air gap as small as is consistent with the good performance of the motor after it is under operating conditions. The beneficial effects upon starting conditions secured by reducing the air gap are not, in the writer's opinion, so great as some believe. See also " Comparison between Induction and Synchronous Motors at Starting."

5. To reduce, as much as is consistent with first cost and performance, the resistance of the stator windings. This not only reduces the electromotive force required to produce the requisite starting torque, but also lowers the power input to the motor during the starting period.

The five factors given above are in the order of their importance, according to the writer's judgment.

To facilitate the reading of the paper, the derivations of such formulas as may be useful in the final calculation of the starting conditions, but which do not lead directly to the derivation of the final equations, have been appended. This applies to the derivation of the equations for leakage reactances, and for the convenience of the reader the final results are repeated in the main body of the paper.

SELF AND MUTUAL INDUCTION

With the rotor of a synchronous motor stationary, the circuits are essentially those of the primary and secondary of a transformer with great leakage between its members and large magnetizing current. The secondary is short-circuited in that the currents are caused to flow through the amortisseur winding, or in the solid masses in the form of eddies.

The values of these currents must be equal to the voltages induced, divided by the impedances of their paths, and the time-phase position in every case is such that the tangent of the angle of lag of each current behind its voltage is equal to the reactance divided by the resistance. In other words, we must consider the relations of the same factors which obtain in a transformer with a short-circuited secondary.

It has been found from numerous tests that the apparent inductance of coils lying in slots opposite the pole heads is greater than that of those lying between the poles. It would appear from this that the self-induction of the former is greater than that of the latter. With an amortisseur winding on the rotor, this is true to a limited extent only. Emanating from those coils opposite the pole heads, leakage fluxes from the teeth pass into the heads of the poles without interlinking with any of the rotor conductors. This is entirely leakage flux which we designate as zigzag leakage. There is, however, an additional flux which does interlink with the rotor conductors and would apparently increase the inductance of the stator, inasmuch as the current for the same voltage is decreased thereby. However, this flux produces mutual, rather than self-induction, and may be productive of torque, whereas the self-inductive flux has the effect of increasing the drop in the stator without assisting in the production of torque.

Tooth tip leakage, which we have distinguished from the zigzag leakage, arises from those coils which lie in slots between the the pole heads. After emerging from the teeth, tooth tip leakage flux has air only for its path, whereas zigzag leakage flux has the air gap and part of the pole head for its path. Were it not for the mutual flux, which in general is productive of torque, the apparent reactance would not be very different for the various positions of the rotor. This will be seen at once, when one considers that a great portion of the leakage of the stator is made up by the flux which crosses the slot and that which encircles the end connections.

If the rotor be not provided with an amortisseur winding and the poles and field ring be so well laminated that no appreciable currents flow in any parts thereof, a large flux will pass through the poles and field ring and will cause a larger apparent reactance in the coils opposite the pole heads than in the intermediate ones. Since there are negligible currents in the rotor, it would hardly be correct to consider this as mutual flux, but rather as self-inductive flux only. In a similar way, with a solid field ring and laminated poles, the flux which passes as leakage from pole to pole must be considered as self-inductive and not mutual flux. In this case that flux only is mutual which passes into and interlinks with the various conductors carrying eddy currents in the solid field ring.

Inasmuch as the voltage induced in the field coils reaches a very high value with laminated rotor construction, it is evident that the flux which passes through the poles reaches considerable magnitude. This is the mutual flux which is productive of torque and is the chief cause of the unbalance in the currents in the stator. For further discussion of this see " Non-uniformity of Torque at the Instant of Starting," " Unbalance in Phases," and " Star and Delta Connection."

EFFECTS OF HYSTERESIS

Any loss which occurs in the rotor at the instant of starting will tend to bring the current more nearly into time phase with the flux and thus materially assist starting. Whether this loss is due to hysteresis or currents induced in the rotor is immaterial, as both tend to reduce the angle of lag of the current behind the electromotive force which produces it.

If we were completely to laminate the rotor structure and depend upon hysteresis rather than eddy currents, very little torque would be obtained. It is for this reason that we provide paths through which the currents may flow, which will be influential in producing torque.

The hysteresis loss is so small, in general, in comparison with circulating currents, that we may entirely neglect it. This is customary in connection with induction motors and, as is well known, no appreciable error is introduced by following out this method.

NON-UNIFORMITY OF TORQUE AT THE INSTANT OF STARTING

If two pieces of steel or other magnetic material be placed opposite each other and one of them be magnetized so that a consequent pole is induced in the other, then the two pieces will tend to move into such position as to reduce to a minimum the reluctance of the path through which the flux passes in going from one piece of steel to the other.

Applying this principle to the case of the motor in question, it will be seen that if the polar arc has such length that for some positions of the rotor the reluctance of the flux path through the air gap is different from that for other positions, then there will be a variation of torque in the different positions of the rotor for the same input to the stator. It is very important, therefore, in proportioning the parts of the rotor body, to make the polar arc of such length that the reluctance of the air gap path will be nearly uniform, regardless of the position of the rotor with respect to the stator. If the rotor should be in the position of minimum reluctance, then the magnetic forces will tend to hold it there, whereas the in-phase currents which flow in the various rotor circuits will tend to produce rotation of the rotor. It will be essential for the forces produced by these currents to overcome the magnetic attraction in addition to the resistances offered to the motion of the rotor before the rotor will begin to turn.

Those who have designed induction motors will appreciate how much the torque will vary for different positions of the rotor, if the number of slots in one member is an exact multiple of those in the other. For example, if we were to take the most striking case of having an equal number of slots in the stator and rotor, then the currents flowing in the conductors set up magnetic fields which tend to hold the rotor in the position of minimum reluctance; that is, with a tooth in the rotor opposite a tooth in the stator.

Applying this to the synchronous motor, it will be seen that if we were to use a squirrel cage winding with the angular distance between slots in the poles equal to the angular distance between slots in the stator, then the currents which would be produced would likewise tend to hold the rotor in the position of minimum reluctance. The worst case occurs when the rotor bars are exactly one stator slot pitch apart; but there would be considerable variation in torque nevertheless, if the bars were spaced one-half slot pitch, or two slot pitches, or any other multiple of the stator slot pitch.

It is well known, in general, that the variation in starting torque is minimized in induction motors if the rotor resistance is high compared with its reactance. In other words, the forces due to the in-phase current become large compared to those produced by magnetic attraction between the rotor and stator. For example, slip-ring induction motors, which have 50 per cent variation in starting torque with the rotor short-circuited, have nearly uniform torque with such resistance in series with the rotor as to give normal full load torque at starting.

This applies also to the case of synchronous motors. The writer knows of a certain motor in which the tendency to have locking points due to this source would have been very great, but which in point of fact amounted only to 14 per cent, chiefly due to the fact that the squirrel cage winding was of high resistance as compared with the rotor reactance.

If the spacing between the rotor bars is not a multiple of the stator slot pitch, the air gap being small and the stator slots large, there may be a tendency for the bars to heat unduly when the motor is in synchronism, as the result of the variation in flux between the bars caused by the tufting from the stator teeth. To space the bars other than a definite multiple of the stator slot pitch may create considerable losses and excessive temperature rise. To determine the spacing of the bars in the poles, the designer should call upon his judgment.

There is one other case of which the writer knows that may produce a large variation in torque for the same input to the stator, which is given under " Star and Delta Connection " and will not be repeated here.

UNBALANCE IN PHASES

It is evident that the coils in the stator, which at the instant of starting are directly opposite the pole faces, will have more flux interlinked with them than those coils which are between the poles. This will produce a greater counter electromotive force per ampere in those coils which are opposite the poles than in those between the poles, and therefore less current will flow in the former than in the latter. It will be seen, therefore, that the phases are badly unbalanced at the instant of starting in any definite pole synchronous motor.

As tests which have been made upon motors at rest indicate that this apparent reactance frequently varies about 50 per cent between the two positions, the currents will be correspondingly unbalanced, although not to the same extent that the reactance is greater in one extreme than in the other.

The unbalance in currents also causes an unbalance in impressed electromotive forces, the extent of which is not only dependent upon the difference between currents in the various phases, their magnitude and power factor, but also upon the voltage regulation of the source of supply. In general, the more the impressed electromotive forces are unbalanced by the currents, or the poorer the regulation, the less will the currents be unbalanced.

If the stator be wound with the usual six-phase winding connected for three-phase star—that is, if each phase belt be distributed over 60 electrical degrees—then it will be possible for two of the phase belts to be directly opposite the poles and the third phase belt to be between the poles, so that the current which flows in the phase between the poles will be considerably greater than the currents in the other two phases.

By using the ordinary three-phase winding and connecting it star—that is, using a winding in which each phase belt is distributed over 120 electrical degrees—the unbalance would in all probability be much less. However, this method of winding is hardly to be recommended, as the motor would thereby be handicapped in many ways.

In all the calculations which are made, the final value of current obtained is the r.m.s. value of the currents in the various positions and in the different phases. The same applies to the electromotive forces. In working up results from tests, the r.m.s. value was used rather than the average for all currents and electromotive forces.

In the case of three-phase machines the input in volt-amperes was taken to be the product of the square root of three, the r.m.s. values of the currents and the electromotive forces.

The unbalance would in all probability be considerably greater if delta connection were used. This is taken up under the next subject.

One effect of the unbalance in phases would be to cause the rotating field to depart from one of constant magnitude and thus to some extent lower the starting torque. It is well known that anything which upsets the uniformly rotating field may give rise to losses which do not assist toward producing starting torque. This is one of the discrepancies which the designer must continually have in mind when he proportions the parts of the motor with a view of obtaining good starting conditions.

STAR AND DELTA CONNECTION

If the stator is wound for three-phase and each phase belt covers 60 electrical degrees—that is, if the winding is six-phase rather than three-phase—and the connections are star, then the low apparent reactance of one phase as compared with the others will not cause so much unbalance in currents as would be the case were the electromotive forces applied to each phase on each leg individually. For example, if the phase belt of one of the phases is between the poles and the other two phase belts are opposite the poles, the higher reactance of the latter two phases will influence the current in the first phase and prevent its reaching so high a value as would be the case were the neutral point of the motor connected directly to the neutral point of the transformers or generator. This will cause the rotating field which is produced, to be more nearly constant in magnitude than would be the case were the phases very badly unbalanced by connecting to the neutral point, with the net result that starting conditions would be much better with star connection and three leads than would obtain with star connection and the neutral connected to the neutral of the source of supply.

If the stator be delta-connected, then it would be possible for one phase belt lying between the poles to have comparatively small reactance and have the current in that portion reach a relatively high value. The currents in the other phases, due to the high reactances of their paths, would be low. The result of this bad unbalance would be poor starting conditions in some positions of the rotor and good starting conditions in others. It will be seen, therefore, that in general delta connection should, if possible, be avoided for self-starting synchronous motors, unless the machine be connected star during the starting period. Tests on a delta-connected stator bear out the statements made in reference to the large unbalance and great variations in torque.

In general it is assumed that phase belts cover 60 electrical degrees. This, however, does not apply to real three-phase windings in which the phase belts cover 120 electrical degrees, such as are used in three-ring synchronous converters. In these, unless the pole enclosure be small, some of the conductors in each phase must be under portions of the poles, regardless of the relative positions of poles and armature. The unbalance, therefore, is by no means so great as with a six-phase winding, delta-connected, and the starting conditions are much improved, due to a more uniform torque in the various positions. The writer has not investigated starting characteristics with this type of winding.

In the calculations given in this paper no allowances have been made for the use of delta connection which may unbalance the phases so badly as to make the starting torque less than the power input to the stator minus the losses in the stator. For further discussion of this point, see " Unbalance in Phases."

HIGHER HARMONICS

As has frequently been noted, the higher harmonics in induction motors may produce a rotating field in the opposite direction to that of the fundamental and thus either materially reduce the starting torque or actually cause the rotor to revolve in the reverse direction. They may also cause the rotor to reach a certain fraction of synchronous speed, at which point the higher harmonics may have such an influence as to prevent the rotor accelerating beyond that point.

So far as could be determined, in all synchronous motors on which we have made tests we have not found any one in which the torque at the instant of starting was reduced by higher harmonics. In certain cases, however, when the fields were short-circuited, the motors refused to accelerate beyond half speed until their field circuits were opened. This may have been due to the effect of higher harmonics, but we are unprepared at the present time to say with certainty whether or not this was the cause of the reduction in torque at this point. One reason for believing that it may have been due to this cause is that the effect of the higher harmonics is practically eliminated·if high resistance is introduced into the rotor circuit. With the fields short-circuited, the reactance is extremely high as compared with the resistance, so that the influence of the higher harmonics would be far greater than with the field circuit open.

POLARITY AFTER COMING INTO SYNCHRONISM

After the synchronous motor has been started from rest and locks into synchronism without any current in the field coils, the polarity of the poles in the rotor no longer reverses, inasmuch as the magnetomotive force is produced by currents in the stator and the resultant flux revolves synchronously with the rotor. There is, therefore, a possibility of the polarity being reversed by applying direct current after the motor has come into synchronism. The probability is just about as great that the polarity produced by the direct-current excitation will be the same as that which results after the motor locks into synchronism, as that the reverse condition will obtain.

The magnetomotive force produced by the direct-current excitation in opposition to that produced by the alternating current in the stator will cause the flux to drop to zero for a moment and the torque to disappear instantaneously, with the result that the motor will slip a pole and then, the two magnetomotive forces being additive, the rotor will remain in this position with respect to the rotating field produced by the stator currents.

This will cause an instantaneous rush of current and may set up mechanical stresses which may be very objectionable, even though they last for a very short period. If the number of poles be large, the instantaneous increase in current and production of mechanical stresses will seldom be serious; if, on the other hand, the number of poles be small, this may be sufficiently objectionable to necessitate precautions being taken. The use of a reversing switch for the fields which, has been suggested the operator can manipulate in case the stator ammeter indicates a great rush of current at the instant the field switch is closed. It would of course be essential to use discharge resistance in conjunction with the field so as to permit rapid opening after the circuit has been closed. Another suggestion is to excite the fields slightly, shortly before the motor locks into synchronism. This not only insures the motor coming into step, but also increases the torque near synchronism.

FIELD CONNECTIONS AT STARTING

If the fields were short-circuited during starting, a current would flow in them which is nearly in quadrature with the voltage which is induced in them. This will be at once apparent when one considers the fact that the fields have very high reactance as compared with their resistance. This current will have a decidedly detrimental effect upon the starting conditions, as large stator currents must flow to neutralize the magnetomotive forces of the currents in the field coils. These produce large drops in the stator coils and as a result the input to the stator would be much greater for the same starting torque. For this reason the fields should by no means be short-circuited at the instant of starting.

The most favorable conditions, as far as current input for a given starting torque is concerned, would be obtained by placing in series with the field coils a non-inductive resistance which is equal in ohms to that of the reactance of the fields. This, however, is hardly to be recommended, as a rheostat of several hundred ohms, insulated for about double the induced voltage, would be required, and this would be very expensive and cumbersome.

The best method is to leave the fields open, and if this is done the conditions are not much worse than by having in series with the fields a resistance equal to the reactance. The objection to this method is that the voltage induced in the rotor is so high that it may cause the insulation to be punctured. If the fields are wound for 125 volts and insulated for 5000 volts, this voltage is seldom dangerous in this respect.

When the fields are wound for 250-volt excitation or higher, the voltage induced with laminated pole structure may be prohibitively high and heavier insulation may be required on the rotor. With solid poles, however, the voltage induced in the rotor is very much less than with laminated poles, and even when fields are wound for 250 volts and insulated for 5000 volts they are perfectly safe during the starting period. A means for overcoming the danger of breakdown of insulation in synchronous converters with laminated poles has frequently been used and consists in using a field break-up switch which causes the various field coils to be disconnected from one another.

EFFECT OF TEMPERATURE

The currents which flow in the rotor circuit during the starting period cause the rotor conductors to heat considerably. The increase in temperature increases the resistance of the conducting paths, which in turn augments the losses. This increment in losses tends to increase the temperature, so that it is essential to take observations very rapidly in order to secure reliable results. This is quite noticeable in its effect upon torque, especially when the pole shoes are made of solid material, such as cast steel, which has a high temperature coefficient.

Readings taken of the input to the stator when the poles were comparatively cold indicate, in general, a lower torque than that which would be obtained by means of a brake, probably due to the fact that less time would be required to take input readings than to take brake readings. This is usually more noticeable when the torque is produced by eddy currents induced in solid metal than when the torque is secured by currents in copper bars in a laminated structure, because in the former the eddy currents are confined to a very thin shell and thus tend to produce excessive local heating in the solid structure; and, secondly, because the change in resistance with temperature is very great for steel or cast iron.

The stator coil temperature is also increased while the static torque tests are being made, and this prevents our determining with accuracy the loss in the stator which should be deducted from the stator input.

. Results of Tests

Figs. 1 to 6 show the results of tests made on a three-phase generator with laminated poles and cast steel field ring and without armortisseur winding, to determine the relations of the various quantities when voltages were applied to the stator with the rotor stationary. These tests were made by the use of a brake, and the bearing friction was allowed for and added to the brake readings so as to obtain the total torque produced.

The poles of this machine were so proportioned that the reluctance of the flux path with a slot opposite the middle of the pole was less than that with a tooth opposite the middle of the pole. Since the rotor tends to move into the position of minimum reluctance, it follows that the torque for a given impressed electromotive force is greater with a tooth opposite the middle of the pole than with a slot opposite the middle of the pole. This is shown clearly in Fig. 1.

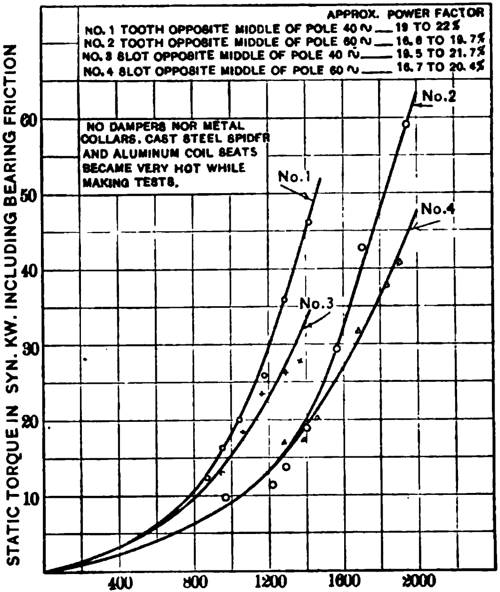


Fig. 1—Variation of Developed Torque with Impressed E. M. F. Without fields

In Fig. 2 the developed torque is plotted against the stator input minus the stator losses. It will be seen from these tests that the torque in the maximum torque position is greater than the input to the rotor, whereas in the minimum torque position it is less, so that the average is very nearly equal to the rotor input. It will also be observed that the torque is proportional to the rotor input in the minimum torque position, whereas it rises more rapidly than the rotor input in the maximum torque position. This is believed to be due to the incremental torque caused by the magnetic pull brought about by the tendency of the rotor to move into the position of minimum reluctance. It may also be affected by the temperature rise of the solid field ring, which became very hot while making the tests.

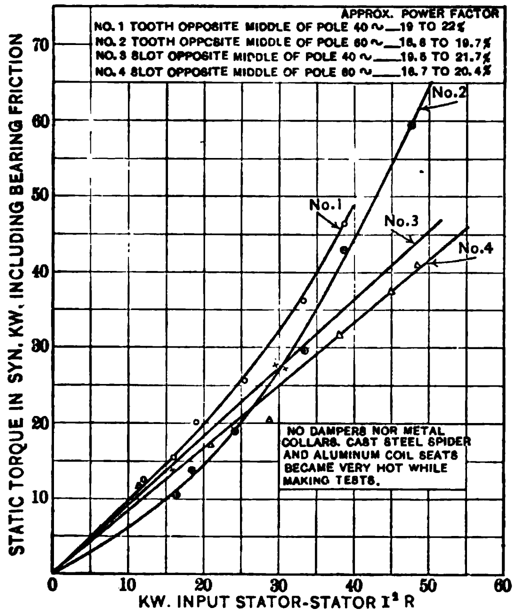


Fig. 2—Variation of Developed Torque with Approximate Input to Rotor

E.m.f. varied; torque measured with brake; without fields

In Fig. 3 the equivalent of the rotor input is plotted against the resistance which was connected in series with the rotor circuit. The fields were wound for 120 volts direct-current excitation and were connected two-circuit during this test so as to reduce as much as possible the resistance which was required. It will be seen from this how very undesirable it is to have the fields short-circuited.

In Fig. 4 are plotted additional curves with resistance in series with the field circuit, which indicate that for a certain resistance (which is nearly equal to the reactance of the rotor) the maximum loss in the field circuit is obtained. This should also give, from a theoretical point of view, the maximum starting torque. However, it will be seen that this differs very little from that which would be obtained by leaving the field circuit open.

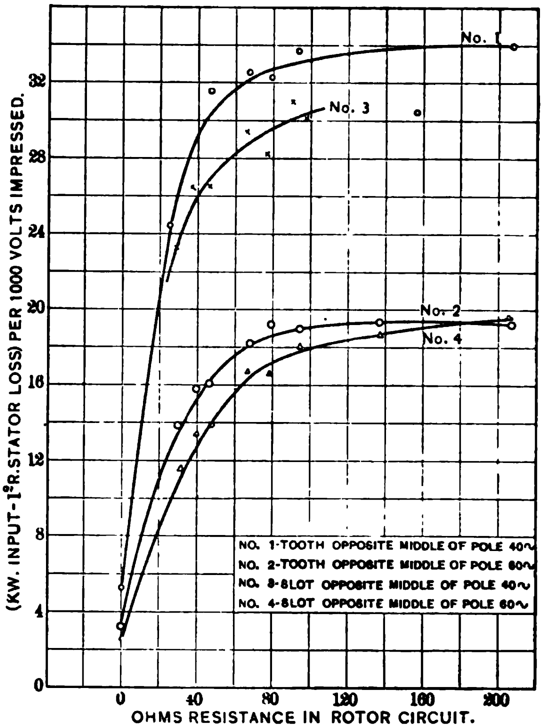


FIG. 3—VARIATION OF ROTOR INPUT WITH RESISTANCE IN FIELD CIRCUIT
Fields connected two-circuit during tests; no dampers nor metal collars

In Fig. 5 the marked effect of the resistance in the rotor circuit upon the power factor is illustrated, and it will be observed how great is the influence of the power factor upon the starting characteristics. On the same curve sheet the stator input in current is shown, which indicates that the current decreases slightly with increased resistance, and thus we have obtained for a given impressed electromotive force, not only an increase in torque, but a decrease in stator current as well, by increasing the non-inductive resistance in the rotor circuit.

In order to complete the experiments, tests were also made with copper bars through the heads of the poles and with metal collars between the field coils and the pole heads. The results of these tests are shown in Fig. 6. Even with these circuits the curves show that the extent of the resistance in series with the field winding has a marked effect upon the starting characteristics.

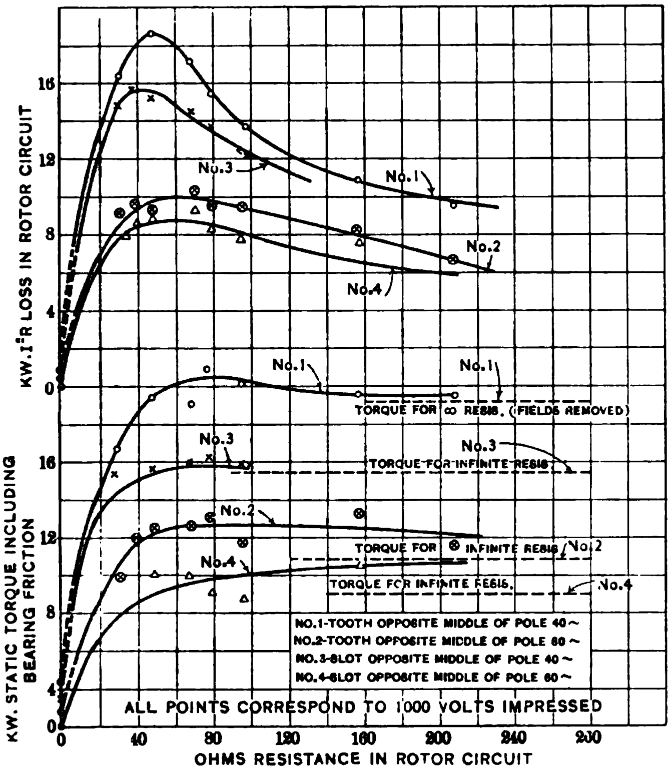


FIG. 4—VARIATION OF ROTOR I^2R LOSS AND TORQUE WITH RESISTANCE IN FIELD CIRCUIT
Fields connected two-circuit

The curves in Figs. 1 to 5, inclusive, also show clearly the effect of frequency upon the starting characteristics of synchronous motors. They illustrate that, although the torque is greatly increased for a given impressed electromotive force at the lower frequency, this is the result of the increase in mutual flux and the gain in power factor due to the reduction in the counter electromotive force of self-induction, the resistance remaining constant.

Motors During Acceleration

It has often been believed that if a synchronous motor is capable of breaking loose from rest, it will have little difficulty in reaching synchronism. This, however, will depend upon the nature of the load, and in order to determine the characteristics of the synchronous motor during acceleration, speed-torque curves were taken of a large generator used as a motor, which was provided with laminated poles, amortisseur winding and cast iron field ring. The curves were also taken on a small, high-speed, 60-cycle generator with solid cast steel rotor. In each case the synchronous machine was operated as a motor from a

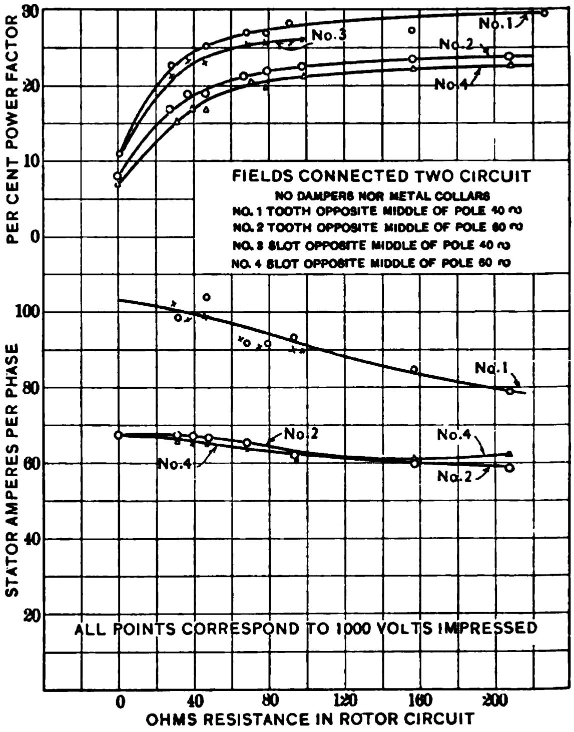


Fig. 5—Variation of Power Factor and Stator Current
With resistance in field circuit

three-phase circuit and was belted to a direct-current generator, which was loaded by allowing it to force current back into the direct-current source of supply. The speed was set by adjusting the field strength of the direct-current generator. The electromotive force at the terminals of the stator of the synchronous machine was then raised to as high a value as was considered permissible, which in turn caused the synchronous machine to increase slightly in speed, this being finally fixed by the amount of power which it was capable of exerting.

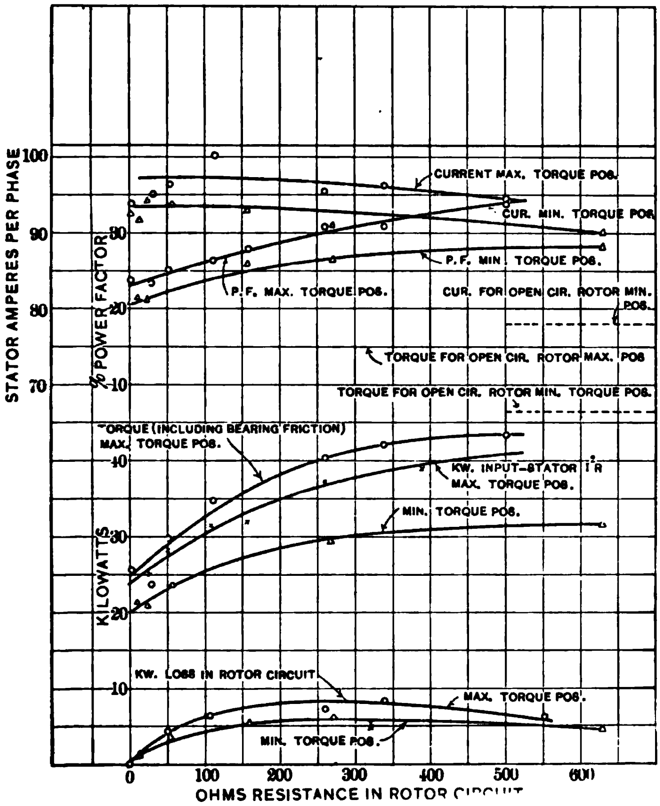


FIG. 6—VARIATION OF STATOR CURRENT, POWER FACTOR AND KW. With resistance in rotor circuit. Poles provided with copper bars and high-resistance metal collars near pole heads.

The power input to the synchronous machine was measured by means of wattmeters and the power output of the direct-current generator was determined by means of voltmeter and ammeter in the usual way. Loss curves were taken, which enabled us to bring in the losses in the direct-current generator, as well as those due to bearing friction and windage in the synchronous machine, and allowance was made for the belt loss between the motor and the generator.

Fig. 7 shows the characteristic curves taken on the first synchronous machine with rotor short-circuited and with amortisseur winding. Fig. 8 shows the characteristics during acceleration with the amortisseur winding and open-circuited fields. Fig. 9 gives the results obtained with amortisseur winding removed and the field circuit opened. These curves indicate the marked effect of the amortisseur winding in producing torque.

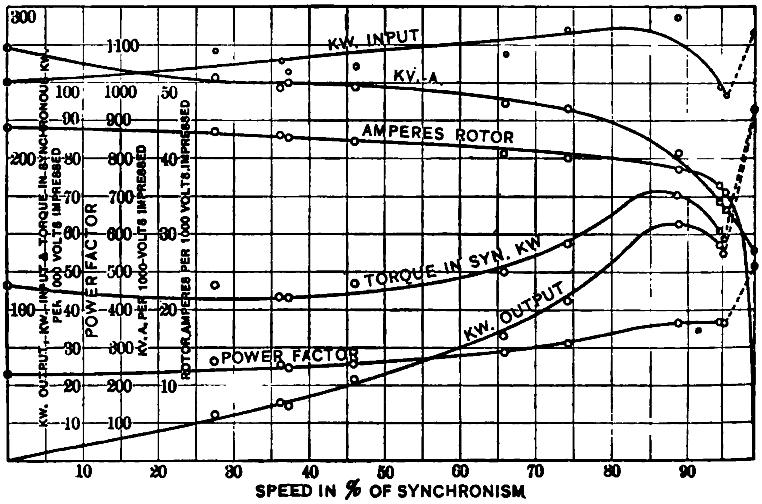


FIG. 7—CHARACTERISTICS OF SYNCHRONOUS MOTORS DURING ACCELERATION

Fields short-circuited with amortisseur winding; laminated poles; solid field ring

In Fig. 10 are given curves of the solid pole machine without amortisseur winding and with the fields open. All of these curves show how greatly the torque is reduced just before synchronism is reached. In order to increase the torque near synchronism, it was found that the application of a small amount of direct current in the rotor will more distinctly define the poles and assist materially in causing the rotor to lock into synchronism. This is greatly dependent upon the excitation applied, and for this reason readings were taken on the solid pole machine with direct current in the fields. The direct current is not the total current which flows in the fields, but is that current which flows when no electromotive force is impressed upon the stator. As soon as there is electromotive force induced by transformer action in the field coils, alternating current flows through the exciter armature and is superimposed upon the direct current which is forced to flow. For example, in one of the curves shown in Fig. 11, the direct current is indicated as 2.85 amperes, whereas the total current in the rotor circuit was approximately 6 amperes.

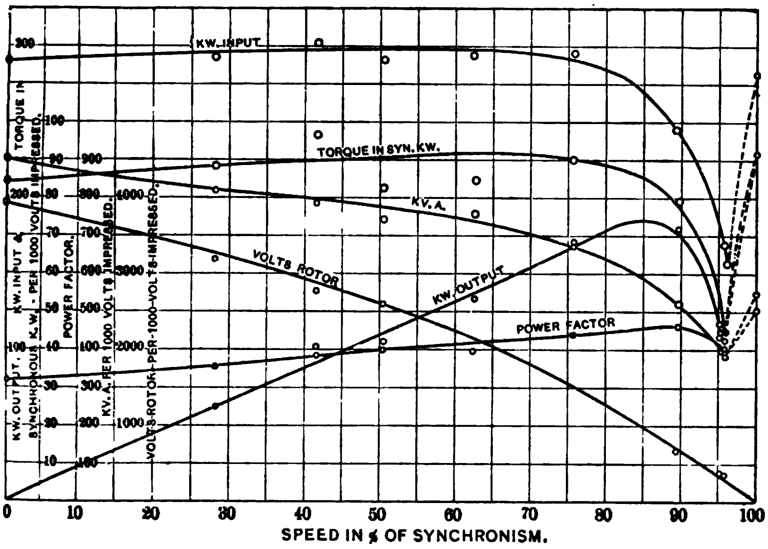


Fig. 8—Characteristics of Synchronous Motors During Acceleration

Open-circuit fields with amortisseur winding; laminated poles; solid field ring

In Fig. 12 is given the effect of speed upon the power factor and volt-ampere input with direct current in the fields.

Fig. 13 shows the effect of variation of exciting current upon the torque, kilowatt input and power factor at 90 per cent of synchronism in the same machine.

The writer has not thoroughly investigated the characteristics of synchronous motors near synchronous speed. It would appear, however, from the tests which have been made, that the following may be deduced:

1. There is a critical direct-current excitation which produces a maximum torque at a definite speed.
2. For best conditions, the exciting current should be increased as the motor accelerates.
3. An increase in exciting current increases the volt-ampere input to the stator.

The writer would explain the phenomenon of dropping off in torque as synchronism is approached, as follows:

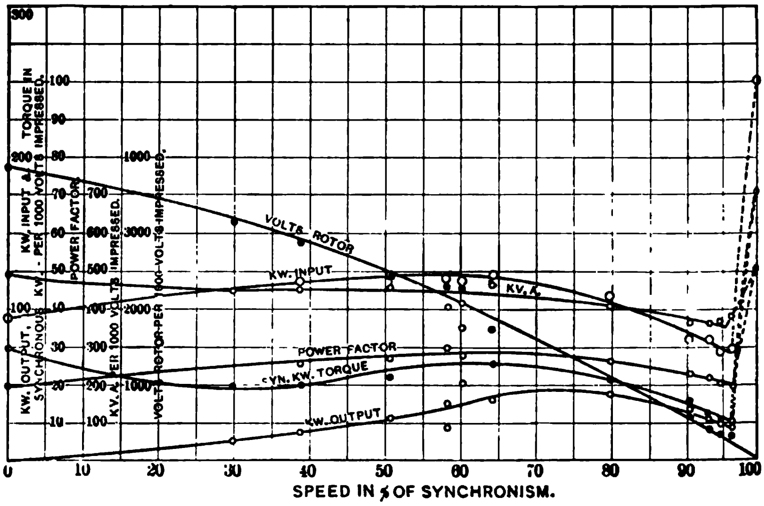


FIG. 9—CHARACTERISTICS OF SYNCHRONOUS MOTORS DURING ACCELERATION

Open-circuit fields without amortisseur windings; laminated poles; solid field ring

In general, in the synchronous motor at any speed the frequency of the rotor currents is equal to the stator frequency minus the frequency of rotation. As the motor speeds up, the rotor frequency diminishes and the electromotive force induced in the rotor conductors decreases with the corresponding diminution in rotor reactance. Up to about 80 per cent of synchronism the rotor currents are not much affected by the change in frequency, due to the lowering of the reactance with the corresponding reduction in induced electromotive force. As synchronism is neared, however, the influence of the lowering of the rotor frequency becomes more and more noticeable, in that the volt-ampere input drops off considerably and the currents which flow in the rotor circuit are too small to exert much torque. (See rotor amperes curve, Fig. 7.)

When within a few per cent of synchronism, currents in the stator produce magnetomotive forces, which, combined with the hysteresis effect in the rotor itself, tend to prevent the polarity reversing and cause the rotor to lock into synchronism. After the motor has reached synchronous speed, it will run as a synchronous motor, even though there be no excitation in the rotor circuit. The magnetomotive force is then obtained from currents in the stator conductors. Flux is produced by this magnetomotive force and rotates at synchronous speed. Due to the fact that the poles are so clearly defined, the polarity of them remains fixed and the motor continues to operate in synchronism with the generator which supplies it with power, and will pull a certain amount of load under these conditions. The effect, then, of exciting the fields with direct current, is to define the poles more clearly, preventing the polarity from reversing and assisting

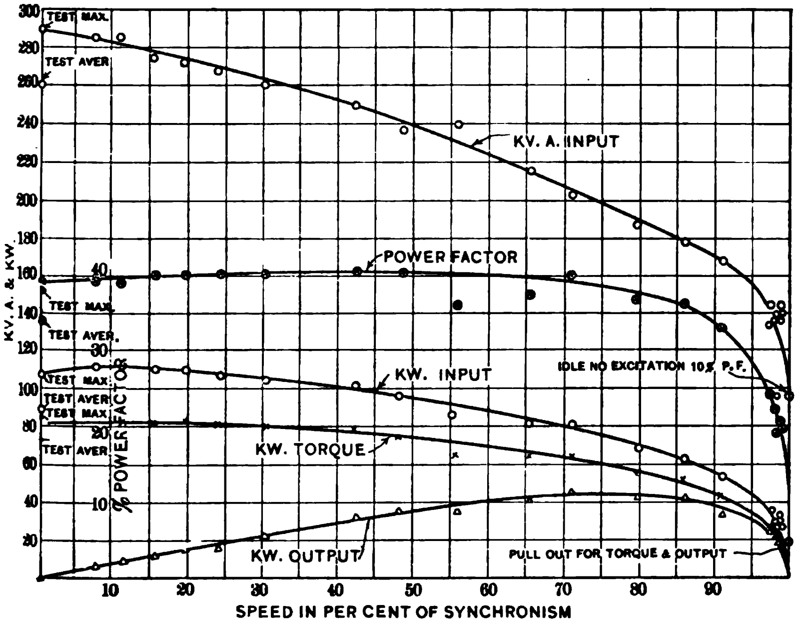


FIG. 10—CHARACTERISTICS OF SYNCHRONOUS MOTORS DURING ACCELERATION
Solid poles; fields open

materially in causing the rotor to lock into synchronism. The cause of diminution of power factor near synchronous speed is believed to be due to the great amount of exciting current, which becomes a very large percentage at this point.

Driving of Fans and Pumps

In starting a fan, the power required to drive it increases approximately as the cube of the speed, and the torque as the square of the speed. A very small torque is required to start the fan—only sufficient to break it loose from rest and overcome the bearing friction. As it approaches synchronism, however, a large amount of power is required.

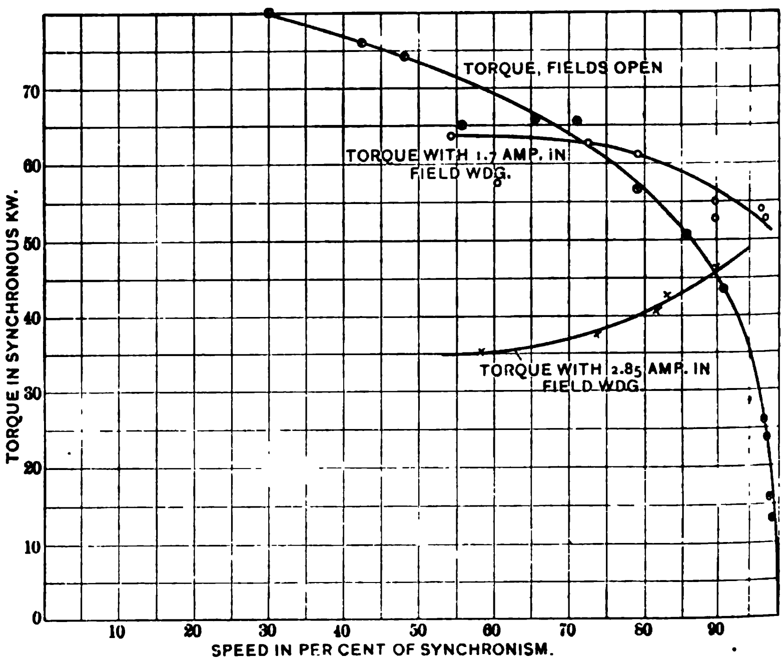


Fig. 11—Speed-Torque Curves
With solid poles

In the case of a centrifugal pump, it is generally claimed that it is dangerous to start unless the pump is full of water, as otherwise, with the small clearances which are needed to obtain high efficiencies, the pump would heat to such an extent as to cause the rotating and stationary members to come into contact and destroy each other. It is also claimed that in order that the pump may begin operating, it should be primed during acceleration.

There is a diversity of opinion among centrifugal pump manufacturers as to the amount of torque which is required to rotate the moving element at synchronous speed with the pump full of water, and the outlet valve closed. The power under such

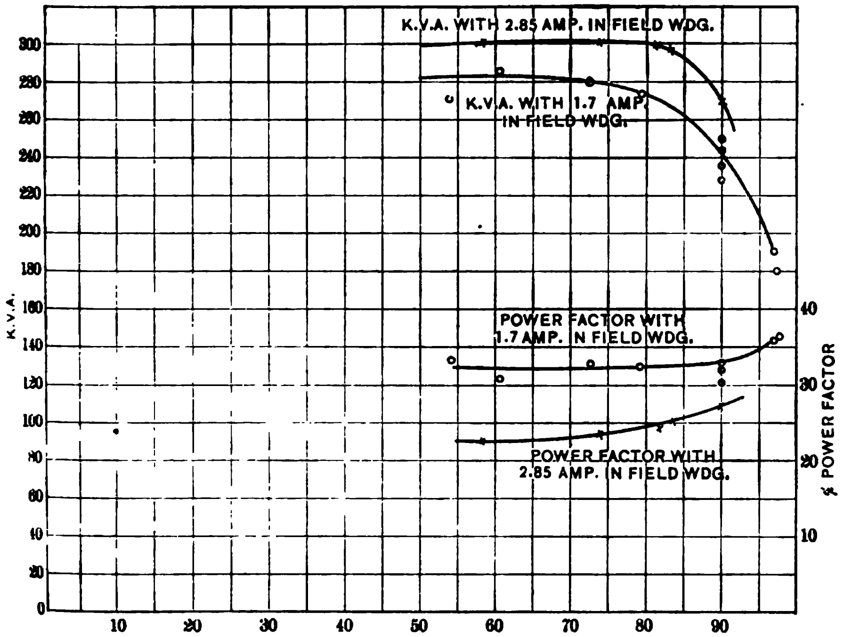


Fig. 12—Effect of Varying Speed on Kv-a. Input and Power Factor
Solid poles

conditions would be absorbed in heating the water, but as this is for a short period it seldom does any harm.

According to the information which it has been possible for the writer to obtain, this torque varies from 35 per cent to 100 per cent of the torque required to operate the pump under normal conditions. In general a synchronous motor should not be counted upon to exert large torque near synchronism, although if direct current is supplied to the rotor, as described under

" Motors During Acceleration," the torque near synchronism can be considerably augmented. Even so, the motor will pull into synchronism only by drawing a large amount of current from the line. and may overheat when it is used to drive a pump or a fan, due to the great quantity of power and current required as synchronism is approached. Sufficient tests have not been made to enable any definite statement to be made in regard to this, and it is believed that a careful investigation of this subject would be productive of fruitful results.

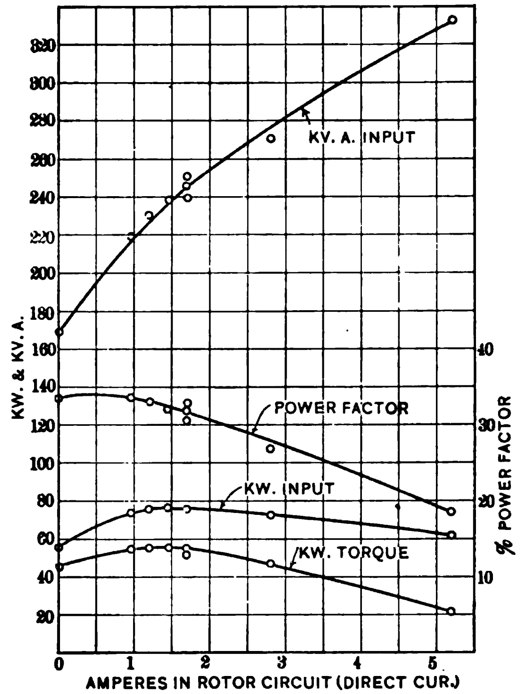


FIG. 13—EFFECT OF VARYING EXCITING CURRENT AT 90 PER CENT OF SYNCHRONISM
Solid poles

The above is based upon the assumption that the motor is direct-connected or belted to the fan or pump. Conditions are entirely different, of course, if a clutch be used.

STARTING OF MOTOR-GENERATOR SETS

The torque required to start up a motor-generator set can be easily determined by allowing for the static friction in the journals at the instant of starting. From a number of tests which have been made to determine the value of the coefficient of friction when all the oil had been allowed to run out of the journals, it has been found that this factor has a minimum value of 0.2 and seldom exceeds 0.3. Therefore, if we allow 0.3 for the static coefficient of bearing friction, it should be safe in determining the torque required to break the set loose from rest. The following formula will then give the starting torque, where μ equals the coefficient of friction, D equals the average shaft diameter in the bearings in inches, W equals the weight in pounds of the complete revolving element, rev. per min. is the revolutions per minute at synchronous speed, and P equals torque expressed in synchronous kilowatts required to start the set.

$$P = \frac{0.746\,\mu\, W \pi D \text{ (rev. per min.)}}{12 \times 33{,}000} = \frac{\mu\, W D \text{ (rev. per min.)}}{169{,}000}$$

GENERAL LAWS TO BE DEDUCED

For perfectly stable conditions, from the tests which have been made, we can usually consider, other things being equal, that the following are approximately correct:

1. The starting torque varies as the square of the impressed voltage.
2. The current varies as the first power of the voltage.*
3. The volt-ampere input varies as the square of the voltage.*
4. The power input varies as the square of the impressed voltage.
5. The power factor is independent of the impressed voltage.
6. The voltage induced in the rotor circuit is proportional to the first power of the impressed voltage.
7. The total loss in the rotor circuit is a reasonably exact measure of the torque developed.

DETERMINATION OF STARTING TORQUE WITH SOLID POLES

The current which flows in the stator of a synchronous motor when a polyphase electromotive force is applied to it, is equal to that voltage divided by the impedance. This impedance, with the motor stationary, consists chiefly of reactance, which appears in both the stator and the rotor. If we were to measure

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*Due to saturation of the paths of leakage flux, as well as to increase in resistance with temperature, the current does not necessarily vary as the first power of the voltage. The effect of saturation of leakage paths is especially noticeable with solid poles.

the reactance of the stator with the rotor out, using a single-phase current applied between neutral and terminal, in the case of a three-phase machine, and applied to one of the phases in the case of a two-phase machine, we would find that with the rotor in, the current which flows bears a nearly definite relation to the electromotive force divided by the reactance which is measured with the rotor removed. Hence this at once gives us the means for determining from experiment what the kilovolt-ampere input will be with the rotor stationary, provided we know the stator reactance.

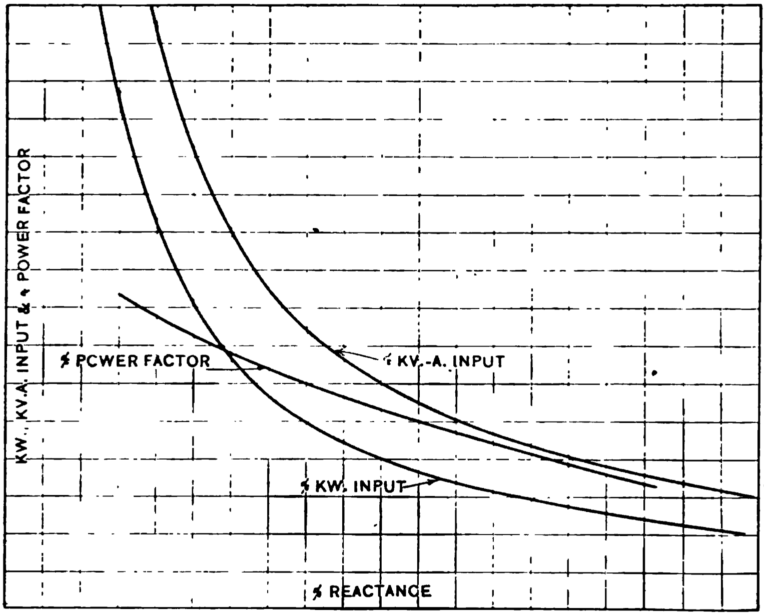

Fig. 14—Kw., Kv-a. Input and Power Factor as a Function of Reactance

In Fig. 14 are shown the forms of the curves obtained by plotting the kilovolt-ampere input against percentage reactance for solid pole machines. It will be seen that if the reactance is doubled, the kilovolt-ampere input is reduced to one-half. In other words, it has been found that this curve approximates an equilateral hyperbola.

It is not exactly correct to plot the power factor of the incoming current against the percentage reactance, since, if the rating of the machine were changed, the percentage reactance would be correspondingly altered while the power factor would not be affected. Nevertheless, the machines from which the points for power factor were plotted were designed on similar lines and they gave a reasonably smooth curve. It is evident that the power input to the stator is the power factor multiplied by the volt-ampere input, so that we obtain the power input curve by multiplying the ordinates of the other two curves. This gives us a very rapid and quite accurate means of predicting the current and power which is taken in by a synchronous motor at the instant of starting, if we know the reactance. The starting torque is then obtained directly by deducting the losses in the stator from the power input.

These curves are plotted from tests made on two- and three-phase, 25- and 60- cycle motors with solid steel poles. It appears that for a given percentage reactance, the difference in number of phases and in frequency has little influence.

These curves are intended to apply to the input with normal voltage impressed upon the stator. If this voltage is reduced by means of an auto-transformer, the power and volt-ampere input are reduced in proportion to the square of the voltage, whereas the power factor remains the same.

These curves have been obtained from machines in which the field circuit was opened at the instant of starting.

In order to predict the reactance of the stator, a formula for this has been derived, which appears in the appendix and is repeated here, as follows:

$$X_s = \frac{7.9 \sim p\, a^2 S\, \lambda_s}{10^8} \Bigg\{ \left(1 - \frac{3}{4}\, \frac{\beta n}{180^\circ}\right) \left[\frac{d_1}{3 W_s} + \frac{d_2}{W_s} + \frac{2\, d_3}{W_s + b_s} + \frac{d_4}{b_s} + \log_{10}\left(1 + \frac{\pi\, W_t}{W_s}\right) + 2 \log_{10}\left(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\right)\right] + 0.4\, s\, \phi_f \left(\frac{M.T.}{\lambda_s} - 2\right) \Bigg\} \qquad (1)$$

For the meaning of the symbols given in this equation, see "Notation," pages 559-561.

DETERMINATION OF STARTING CHARACTERISTICS WITH LAMINATED POLES AND AMORTISSEUR WINDING

The losses which appear in the stationary rotor of a synchronous motor when the field circuit is open and polyphase electromotive forces are applied to the stator, are:

the reactance of the stator with the rotor out, using a single-phase current applied between neutral and terminal, in the case of a three-phase machine, and applied to one of the phases in the case of a two-phase machine, we would find that with the rotor in, the current which flows bears a nearly definite relation to the electromotive force divided by the reactance which is measured with the rotor removed. Hence this at once gives us the means for determining from experiment what the kilovolt-ampere input will be with the rotor stationary, provided we know the stator reactance.

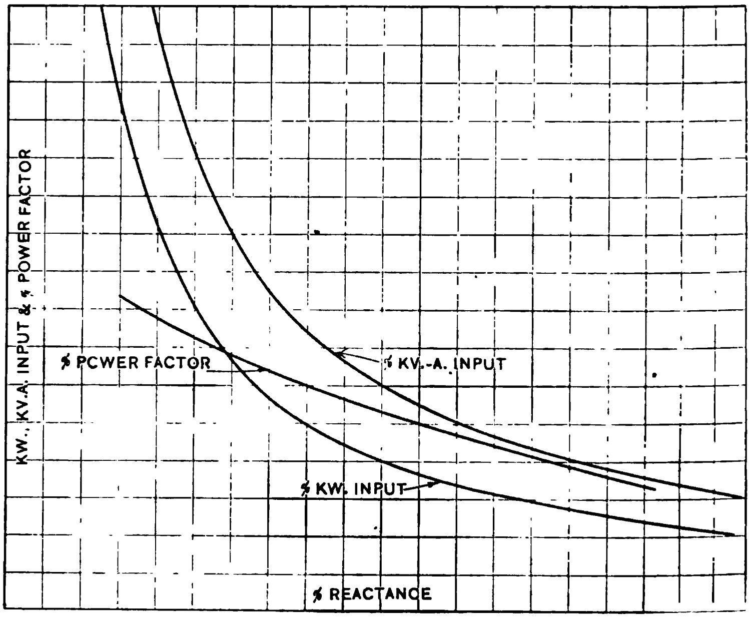

FIG. 14—KW., KV-A. INPUT AND POWER FACTOR AS A FUNCTION OF REACTANCE

In Fig. 14 are shown the forms of the curves obtained by plotting the kilovolt-ampere input against percentage reactance for solid pole machines. It will be seen that if the reactance is doubled, the kilovolt-ampere input is reduced to one-half. In other words, it has been found that this curve approximates an equilateral hyperbola.

It is not exactly correct to plot the power factor of the incoming current against the percentage reactance, since, if the rating of the machine were changed, the percentage reactance would be correspondingly altered while the power factor would not be affected. Nevertheless, the machines from which the points for power factor were plotted were designed on similar lines and they gave a reasonably smooth curve. It is evident that the power input to the stator is the power factor multiplied by the volt-ampere input, so that we obtain the power input curve by multiplying the ordinates of the other two curves. This gives us a very rapid and quite accurate means of predicting the current and power which is taken in by a synchronous motor at the instant of starting, if we know the reactance. The starting torque is then obtained directly by deducting the losses in the stator from the power input.

These curves are plotted from tests made on two- and three-phase, 25- and 60- cycle motors with solid steel poles. It appears that for a given percentage reactance, the difference in number of phases and in frequency has little influence.

These curves are intended to apply to the input with normal voltage impressed upon the stator. If this voltage is reduced by means of an auto-transformer, the power and volt-ampere input are reduced in proportion to the square of the voltage, whereas the power factor remains the same.

These curves have been obtained from machines in which the field circuit was opened at the instant of starting.

In order to predict the reactance of the stator, a formula for this has been derived, which appears in the appendix and is repeated here, as follows:

$$X_s = \frac{7.9 \sim p\, a^2\, S\, \lambda_s}{10^8} \left\{ \left(1 - \frac{3}{4}\, \frac{\beta n}{180^\circ}\right) \left[\frac{d_1}{3 W_s} + \frac{d_2}{W_s} \right.\right.$$

$$+ \frac{2\, d_3}{W_s + b_s} + \frac{d_4}{b_s} + \log_{10}\left(1 + \frac{\pi\, W_t}{W_s}\right)$$

$$\left.\left. + 2 \log_{10}\left(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\right)\right] + 0.4\, s\, \phi_f \left(\frac{M.T.}{\lambda_s} - 2\right)\right\} \quad (1)$$

For the meaning of the symbols given in this equation, see "Notation," pages 559-561.

DETERMINATION OF STARTING CHARACTERISTICS WITH LAMINATED POLES AND AMORTISSEUR WINDING

The losses which appear in the stationary rotor of a synchronous motor when the field circuit is open and polyphase electromotive forces are applied to the stator, are:

1. Losses due to eddy currents in field ring, end plates, rivets, etc.
2. Losses in the rotor bars.
3. Losses in the end rings of the amortisseur winding.
4. Losses due to circulating currents in the metal collars surrounding the poles near the heads, if collars are used.
5. Losses due to currents in the short-circuited end turns of the field coils.
6. Losses due to contact resistance.
7. Losses due to a pulsating component of flux, not productive of torque.

In the following treatment the first three of these only are considered. To bring into the equations the losses due to circulating currents in the collars would cause them to be very involved, and as most synchronous motors with amortisseur windings do not have collars on the rotors, it was deemed best to omit the effect of current in them upon the starting characteristics.

The losses due to currents in the end turns of the field coils are comparable with those in the collars. These losses may reach such magnitude as to cause great local heating, especially if the field coils are made of wire. It is best, therefore, to avoid short-circuiting the end-turns, and to hold them securely by some other means. As far as the detrimental effects upon the starting characteristics are concerned, however, it should be borne in mind that with but one turn at each end of the coil short-circuited upon itself, the magnitude of its resistance is comparable with that of its reactance, whereas this does not hold with the entire coil short-circuited, as the resistance is proportional to the first power, and the reactance to the square, of the number of turns.

The losses due to contact resistance are discussed under " Notes on Determination of Starting Characteristics with Laminated Poles."

The losses in the rotor which are not productive of torque are very difficult to compute. For further discussion of this, see " Unbalance in Phases," and " Star and Delta Connections."

Of the first three losses enumerated above, those due to eddy currents are discussed under " Notes on Determination of Starting Characteristics with Laminated Poles." The writer has had the opportunity to investigate one case only and found this loss to be about 30 per cent of the total rotor loss.

It is first necessary to know how much starting torque is required, and this should include the torque required to overcome the static bearing friction of the motor. All torques and losses should be expressed in synchronous watts (or simply watts). From this total loss, the eddy current loss Pe should be deducted. This then leaves the losses in the bars, P_b, and end rings, $Pe.r.$

NOTATION

a = number of active conductors per slot = number of conductors per slot divided by number of parallel circuits in armature.

$A.T.$ = ampere-turns per pole required to force flux ϕ through magnetic circuit of one pole.

b = number of rotor bars per pole.

b_s = opening at top of slot (for stator or rotor as case may be).

C = Carter fringing coefficient, from curve, Fig. 19.

d_1 = total depth of conductor in slot (for stator or rotor as case may be).

d_2 = depth of slot between top of conductor and top of parallel sides.

d_3 = depth of variable width portion of slot (for partly closed slot only).

d_4 = depth of parallel sides of slot opening (for partly closed slot only).

$D_{e.r.}$ = average diameter of end ring.

E = impressed electromotive force per phase or per leg if star-connected.

E_1 = stator equivalent of electromotive force consumed by rotor bar and end ring resistance.

E_2 = stator equivalent of electromotive force consumed by rotor bar and end ring reactance.

E_3 = stator equivalent of electromotive force consumed by rotor impedance.

E_4 = electromotive force consumed by stator reactance.

E_5 = electromotive force consumed by stator resistance.

E_f = electromotive force induced in field coils.

E_{r_1} = electromotive force consumed by rotor bar and end ring resistance.

E_{r_2} = electromotive force consumed by rotor bar and end ring reactance.

F_b = sectional area of one rotor bar.

$Fe.r.$ = sectional area of end ring.
F_s = sectional area of one stator conductor.
h = linear distance between adjacent rotor bars in same pole.
I = effective value of stator current per phase.
I_b = r.m.s. value of current per rotor bar.
I_0 = magnetizing current per phase corresponding to $A.T.$
I_1 = stator equivalent, in amperes per phase, of current in rotor bars.
$j = \sqrt{-1}.$
k_d = distribution factor = ratio of vector to algebraic sum of electromotive forces in stator conductors in one phase or leg.
K = constant for computing losses in end rings.
L, L_1 etc. = inductances.
m = ratio of vector to arithmetical sum of currents in rotor bars in one-half pole.
M = short pitch factor for use with reactance $= \frac{5}{8}$ for three-phase and $\frac{3}{4}$ for two-phase and single-phase.
$M.T.$ = mean turn of stator coil.
n = number of phases.
N = number of turns per coil in fields.
N_1 = total number of stator slots.
p = number of poles.
p_f = short pitch factor = decrease in electromotive force due to fractional pitch $= \cos \frac{\beta}{2}$
P_b = watts lost by resistance of rotor bars.
Pe = watts lost by eddy current in field ring and other solid portions.
$Pe.r.$ = watts lost by resistance of end rings.
R_b = resistance of one rotor bar.
R_s = resistance of one phase of stator winding.
S = number of stator slots per pole per phase.
t = ratio of transformation of voltage.
u = polar arc.
w_b = weight per unit volume of material in rotor bars.
$w_{e.r.}$ = weight per unit volume of material in end rings.
Wb = watts per unit weight in rotor bars.
$We.r.$ = watts per unit weight in end rings.

W_s = width of main portion of rectangular slot for stator or rotor as case may be.

W_t = width of stator tooth at inner periphery of stator.

X_b = reactance of one rotor bar.

X_f = stator end connection reactance.

X_s = reactance per leg of stator.

X_{s_s} = stator slot reactance.

X_t = tooth tip reactance.

X_z = zigzag reactance.

α = angle of lag of eddy currents in rotor behind electromotive force induced in rotor bars.

β = electrical angle that coils are dropped back of full pitch.

γ = angle between stator equivalent of rotor bar current I_1 and total current I.

δ = angle between stator current I and stator equivalent of rotor impedance electromotive force (E_2).

Δ = radial length of air gap.

θ = angle of lag of total stator current behind the impressed electromotive force = angle whose cosine is power factor.

λ = average slot pitch.

λ_b = axial effective length of rotor bar in pole only.

λ_b' = axial effective length of rotor bar between end rings.

λ_s = axial gross length of stator iron.

ρ_b = resistance of unit cube of material in rotor bars.

$\rho_{e.r.}$ = resistance of unit cube of material in end rings.

ρ_s = resistance of unit cube of material in stator coils.

σ = field ring leakage factor = ratio of mutual flux linking with rotor bars to mutual flux entering field ring.

σ' = field coil leakage factor = ratio of mutual flux linking with rotor bars to average mutual flux linking with field coils.

τ = pole pitch, at average end ring diameter.

τ' = pole pitch, at inner periphery of stator.

ϕ = useful (or mutual) flux per pole linking with rotor bars.

ϕ_f = leakage lines per ampere per unit length of end connections, from Fig. 18.

ψ = angle of lag of current in rotor bars behind electromotive force induced therein.

ω = electrical angle between adjacent rotor bars in same pole. In appendix ω = electrical angle between currents in adjacent phases.

$\sim$ = frequency, cycles per second.

DERIVATION OF FORMULAS FOR AMORTISSEUR WINDING AND LAMINATED POLES

The leakage reactance of each rotor slot, if round slots are used, is

$$X_b = \frac{2\pi \sim \lambda_b{}^{*} 0.4\pi}{10^8}\left(0.62 + \frac{d_4}{b_s}\right) \tag{2}$$

If the slots are rectangular in section,

$$X_b = \frac{2\pi \sim \lambda_b{}^{*} 0.4\pi}{10^8}\left(\frac{d_1}{3W_s} + \frac{d_2}{W_s} + \frac{2d_3}{W_s + b_s} + \frac{d_4}{b_s}\right) \tag{3}$$

For the leakage of the end ring see " Notes on Determination of Starting Characteristics with Laminated Poles."

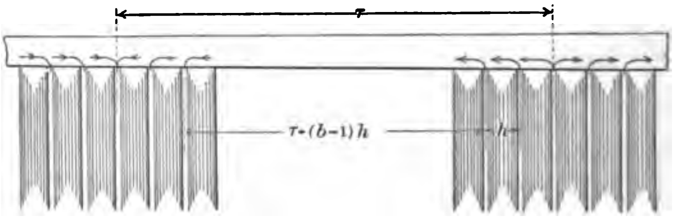

FIG. 15

The resistance of each rotor bar is

$$R_b = \frac{\rho_b \lambda_b'}{F_b} \tag{4}$$

The losses in the bars are given by

$$P_b = I_b{}^2 R_b \, p \, b \tag{5}$$

$$P_b = I_b{}^2 \, p \frac{b \rho_b \lambda_b'}{F_b} \tag{6}$$

In order to calculate the losses in the end rings we shall break the rings into two portions: those portions of the rings between the first and last bars of the same poles, and those portions be-

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*If inches are used throughout, substitute 3.19 for 0.4 π. The derivation of the equation for the round slot will be found in the appendix. The other equation for rectangular slot is well known.

tween the nearest bars of adjacent poles. If all the currents are in phase with one another, the former of these losses is:

$$(Pe.r.)_1 = 4\,p\,\frac{\rho_{e.r.}}{Fe.r.}\,I_b^2\,h\,K \tag{7}$$

where K is a constant depending upon the number of bars per pole (b). See Fig. 15. If there are but two bars per pole, there is no current in the rings between the bars except that due to phase difference between the electromotive forces induced in the bars, which for the present we shall neglect. If the number of bars per pole be three, then the current from the middle bar we assume to divide equally, one-half flowing in each direction. Calculating from the center of the poles and in one ring only, the loss between bars with three bars per pole is proportional to

$$\left(\frac{I_b}{2}\right)^2 = 0.25\,I_b^2. \text{ See Fig. 15.}$$

Similarly for $b = 4$, the losses are proportional to $(1\,I_b)^2 = I_b^2$. For five bars per pole, we have

$$\left(\frac{I_b}{2}\right)^2 + \left(\frac{3\,I_b}{2}\right)^2 = 2.5\,I_b^2 \text{ etc.}$$

The following series has been found to hold for any value of b.

$$K = \left(\frac{b}{2} - 1\right)^2 + \left(\frac{b}{2} - 2\right)^2 + \left(\frac{b}{2} - 3\right)^2 + \left(\frac{b}{2} - 4\right)^2 + \ldots$$

$$\left(\frac{b}{2} - \frac{b}{2}\right)^2 \text{for } b = \text{even.} \tag{8}$$

and

$$K = \left(\frac{b}{2} - 1\right)^2 + \left(\frac{b}{2} - 2\right)^2 + \left(\frac{b}{2} - 3\right)^2 + \left(\frac{b}{2} - 4\right)^2 + \ldots$$

$$\left[\frac{b}{2} - \left(\frac{b}{2} - \frac{1}{2}\right)\right]^2 \text{for } b = \text{odd.} \tag{9}$$

Or, tabulating, we obtain:

NUMBER OF BARS PER POLE	K
2	0
3	0.25
4	1.00
5	2.50
6	5.00
7	8.75
8	14.00
9	21.00
10	30.00

Equation (7) is only approximately correct, as the assumption is made that the currents in the several bars are in phase with each other, so that the vector sum would be less than the arithmetical sum. This discrepancy is offset, however, by the fact that no account is taken of the losses in the rings due to circulating currents between bars in the same pole resulting from a difference in phase between the currents in them.

The loss in the rings between the nearest bars of adjacent poles is given by

$$(Pe.r.)_2 = [\tau - (b - 1)\,h]\,2\,p\,\frac{\rho_{e.r.}}{Fe.r.}\,I_{er}^2 \tag{10}$$

But

$$Ie.r. = \frac{b\,I_b}{2}\,m \tag{11}$$

where *m* is the ratio of the vector sum to the arithmetical sum of currents in bars in one-half of each pole. The following table gives values of *m*.

Number of bars per pole	"*m*"
2	1
3	$\frac{1}{1.5}\sqrt{1.25 + \cos\omega}$
4	$\cos\frac{\omega}{2}$
5	$\frac{1}{2.5}\sqrt{2.25 + 3\cos\omega + \cos 2\omega}$
6	$\frac{1 + 2\cos\omega}{3}$
7	$\frac{1}{3.5}\sqrt{3.25 + 5\cos\omega + 3\cos 2\omega + \cos 3\omega}$
8	$\frac{1}{2}\left(\cos\frac{\omega}{2} + \cos\frac{3\omega}{2}\right)$
9	$\frac{1}{4.5}\sqrt{4.25 + 7\cos\omega + 5\cos 2\omega + 3\cos 3\omega + \cos 4\omega}$
10	$\frac{1 + 2\cos\omega + 2\cos 2\omega}{5}$

In the above "ω" is the electrical angle between adjacent bars in the same pole.

Then

$$(Pe.r.)_2 = [\tau - (b - 1)\,h]\,p\,\frac{\rho_{e.r.}}{Fe.r.}\,\frac{b^2 I_b^2 m^2}{2} \tag{12}$$

Combining equations (7) and (12) we have

$$Pe.r. = (Pe.r.)_1 + (Pe.r.)_2 = p\,\frac{\rho_{e.r.}}{Fe.r.}\,I_b^2 \left\{ 4h\,K + \frac{[\tau - (b-1)\,h]\,b^2\,m^2}{2} \right\} \qquad (13)$$

and the total loss in the bars and rings is

$$Pe.r. + P_b = p\,\frac{\rho_{e.r}}{Fe.r.}\,I_b^2 \left\{ 4\,h\,K + \frac{[\tau - (b-1)\,h]\,b^2\,m^2}{2} \right\} + p\,b\,I_b^2\,R_b \qquad (14)$$

The current per bar is then

$$I_b = \sqrt{\frac{Pe.r. + P_b}{p\left\{ b\,R_b + \frac{\rho_{e.r.}}{Fe.r.}\left[4\,h\,K + \frac{\{\tau - (b-1)\;h\}\;b^2\;m^2}{2} \right] \right\}}} \qquad (15)$$

The above equation enables one to determine the current per bar if the proportions in the amortisseur winding are known. If we are to decide upon them, however, we may use the following method:

We may allow a certain number of watts per unit weight of material in the rings and bars, these being fixed by the permissible temperature rise of these parts at starting and the duration of the starting period. With this in view, we have:

$$\text{Weight, bars} = w_b\,b\,F_b\,\lambda_b'\,p \qquad (16)$$

$$\text{Weight, rings} = 2w_{e.r.}\,\pi\,De.r.\;Fe.r. \qquad (17)$$

Loss per unit weight in bars =

$$\frac{I_b^2\,p\,b\,\rho_b\,\lambda_b'}{w_b\,b\,F_b^2\,\lambda_b'\,p} = \frac{I_b^2\,\rho_b}{w_b\,F_b^2} = W_b \qquad (18)$$

Loss per unit weight in rings =

$$\frac{p\;\rho_{e.r.}\,I_b^2 \left\{ 4\,h\,K + \frac{[\tau - (b-1)\;h]\,b^2\,m^2}{2} \right\}}{2\,w_{e.r.}\,\pi\,D\,e.r.\;F^2e.r.} = We.r. \qquad (19)$$

Solving these equations for F_b and $Fe.r.$, we obtain

$$F_b = I_b\sqrt{\frac{\rho_b}{w_b\,W_b}} \qquad (20)$$

$$Fe.r. = I_b \sqrt{\frac{p\ \rho_{e.r.}\ \{4\,h\,K + \frac{1}{2}\ [\tau - (b-1)\ h]\ b^2\ m^2}{2\ w_{e.r.}\ \pi\ De.r.\ We.r.}} \tag{21}$$

Substituting these values for F_b and $Fe.r.$ and the value of R_b from equation (**4**) in equation (**14**), we obtain, after simplifying,

$$Pe.r. + P_b = I_b[\sqrt{p\,\rho_{e.r.}\,\{4\,hK + \frac{1}{2}[\tau-(b-1)h]\,b^2m^2\}\,2w_{e.r.}.\pi\,De.r.\,We.r.} + p\,b\,\lambda_b'\ \sqrt{w_b\,W_b\,\rho_b} \tag{22}$$

and $I_b =$

$$\frac{Pe.r. + P_b}{\sqrt{p\,\rho_{e.r.}\,\{4\,hK + \frac{1}{2}[\tau-(b-1)h]b^2\,m^2\}\,6.28w_{e.r.}\,De.r.\,We.r.} + p\,b\,\lambda_b'\sqrt{w_b W_b \rho_b}} \tag{23}$$

This last equation enables us to determine at once the current per bar without knowing their sections. These may be found by substituting in equations (**20**) and (**21**) after finding I_b.

The resistance drop in each bar is $= I_b\,R_b$ (**24**)

and

$$\frac{Pe.r. + P_b}{P_b} = \frac{E_{r_1}}{I_b\,R_b} \tag{25}$$

hence

$$E_{r1} = \frac{I_b\,R_b\,(Pe.r. + P_b)}{p\,R_b\,b\,I_b^2} = \frac{Pe.r. + P_b}{p\,b\,I_b} \tag{26}$$

Taking the ratio of transformation of voltages to be the ratio of voltage per leg in the stator to the corresponding voltage in one bar in the rotor, we have:

$$t = a\,S\,k\,p_f\,p \tag{27}$$

and $E_1 = t\,E_{r1}$ (**28**)

$$E_2 = t\,E_{r2} = t\,X_b\,I_b \tag{29}$$

$$E_3 = \sqrt{E_1^2 + E_2^2} \tag{30}$$

In equation (**29**) X_b should be increased above rotor bar reactance so as to include end ring reactance if this latter be of sufficient magnitude.

A better understanding of the manner in which the losses due to eddy currents Pe are brought in, may be obtained by referring to Fig. 16. This illustrates, for simplicity, a hedgehog transformer with a large amount of leakage. The primary winding A corresponds to the stator winding of the synchronous motor;

the secondary winding *B* corresponds to the amortisseur winding of the synchronous motor; and the secondary winding *C* corresponds to the eddy current paths in the field ring, rivets, etc. If we consider the electromotive forces induced by the rate of change of fluxes produced by the exciting magnetomotive force, we see that the electromotive force per turn induced in *C* is smaller than that induced in *B* and also smaller than the counter electromotive force induced in *A*. Nevertheless all three electromotive forces are in time phase with one another. A certain portion of the main primary flux ϕ_1 links with all turns; a second portion ϕ_2 links with *A* and *B* but not with *C*; and a third portion ϕ_3 links only with *A*. Similarly there are leakage fluxes (ϕ_4, ϕ_5 and ϕ_6) due to secondary currents which link only with the secondary and not with the primary circuits. We have seen that the equivalent electromotive force induced in *B* (the amortisseur winding) is given by E_2. The equivalent electromotive force induced in the solid portions (in stator terms) is $\frac{E_2}{\sigma}$ where σ is the leakage factor representing the leakage flux between poles. The value of the various eddy currents equals their electromotive forces divided by their impedances, and they lag behind their pressures by an angle whose tangent is their reactance divided by their resistance $\left(\text{or } \alpha = \tan^{-1} \frac{X}{R}\right)$. Hence, if I_2 is the equivalent stator current of the summation of eddy currents, we have:

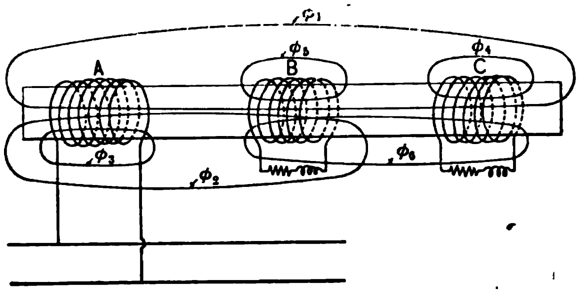

Fig. 16

$$Pe = \frac{n E_2}{\sigma} I_2 \cos \alpha \tag{31}$$

$$\text{or } I_2 = \frac{Pe\, \sigma}{n E_2 \cos \alpha} \tag{32}$$

For the determination of Pe, σ and $\cos \alpha$ see "Notes on Determination of Starting Characteristics with Laminated Poles."

The stator equivalent of the rotor bar current is

$$I_1 = \frac{b\, I_b}{n\, a\, S} \tag{33}$$

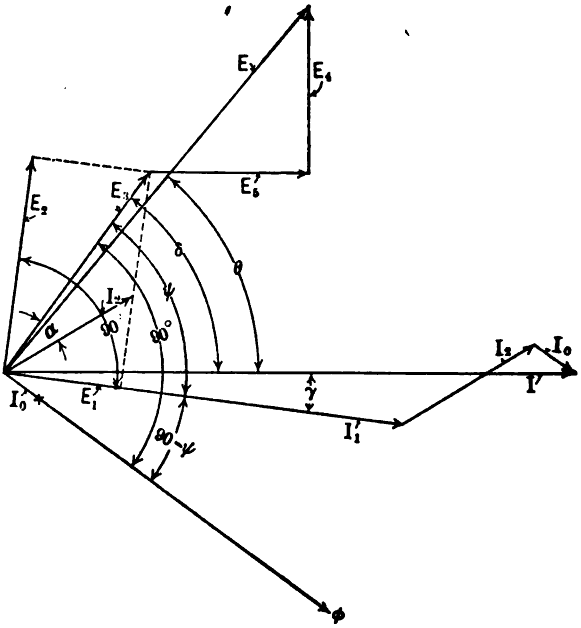

FIG. 17

And the magnetizing current is

$$I_0 = \frac{A.T.}{\frac{\sqrt{2}}{2 \times 2}\, n\, a\, S} = \frac{2\sqrt{2}\, A.T.^{*}}{n\, a\, S} \tag{34}$$

In this equation $A.T.$ can be computed in the ordinary way for determining the ampere-turns required to force flux corresponding to E_3 across the single air gap. The voltage induced in the field coils is

$$E_r = \frac{4.44\, \phi\, N\, p \sim}{10^8\, \sigma'} \tag{35}$$

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*This equation, while slightly in error, is the same as is used frequently for computing the armature reaction. It appears, in Berg's "Electrical Energy," and in other works.

and since

$$E_3 = \frac{2.22\ \phi\ a\ S\ k\ p_f\ p\sim}{10^8} = \frac{2.22}{10^8}\,\phi\ t\sim \tag{36}$$

(See equation (27) for value of t)

$$Er = \frac{2\ N\ p}{\sigma'\ t}\,E_3 \tag{37}$$

The resistance per lag of the stator is

$$R_s = \frac{\rho_s\ (M.T.)a\ s\ p}{2\ F_s} \tag{38}$$

And the leakage reactance is

$$X_s = \frac{7.9^{\dagger}\sim p\,a^2\,S\,\lambda_s}{10^8}\left\{\left(1-\frac{M^{\S}\beta\ n}{180^\circ}\right)\left(\frac{d_1}{3\,W_s}+\frac{d_2}{W_s}+\frac{2\,d_3}{b_s+W_s}+\right.\right.$$

$$\frac{d_4}{b_s}+\frac{0.425\,u\,(W_t+CW_s)^2}{\tau'\,\Delta\,\lambda}+\left(1-\frac{u}{\tau'}\right)\left[\log_{10}\left(1+\frac{\pi\,W_t}{W_s}\right)+\right.$$

$$\left.\left.2\log_{10}\left(1+\frac{\pi\,W_t}{2\,W_s+W_t}\right)\right]\right)+0.4\,S\,\phi_f\left(\frac{M.\,T.}{\lambda_s}-2\right)\Bigg\} \tag{39}$$

It will be seen that

$$E_5 = R_s\,I \tag{40}$$

and

$$E_4 = X_s\,I \tag{41}$$

We are now prepared to combine the various quantities for the determination of the electromotive force, current and power supplied to the motor. Counter-clockwise rotation of *vectors* will be considered positive. See Fig. 17.

[†] If the inch system be used, this should be 20. instead of 7.9.

[§] $M = \frac{5}{8}$ for six-phase winding connected for three-phase; and is $\frac{3}{4}$ for four-phase winding connected for two-phase. β = angle dropped back from full pitch; for example, if there be 12 slots per pole, and pitch of slot 1 to slot 11, $\beta = \frac{2\times 180^\circ}{12} = 30^\circ$. For derivation see appendix.

Take I_1 as zero vector. In phase with I_1 is the stator equivalent of the rotor bar resistance drop, E_1. Leading I_1 by 90 degrees is the stator equivalent of the rotor bar reactance drop E_2, which combined with E_1 gives E_3. Lagging behind E_3 by 90 degrees (that is, leading the induced secondary voltage by 90 degrees) is the flux ϕ. In phase with ϕ is the magnetizing current I_0. Lagging behind E_3 by angle α is I_2. The angle which E_3 makes with I_1 is ψ. That is:

$$\psi = \tan^{-1}\frac{E_2}{E_1} \qquad (42)$$

The angle between I_2 and I_1 is $(\psi - \alpha)$, and

$$\underset{\cdot}{I_2} = I_2 \cos(\psi - \alpha) + j\, I_2 \sin(\psi - \alpha) \qquad (43)$$

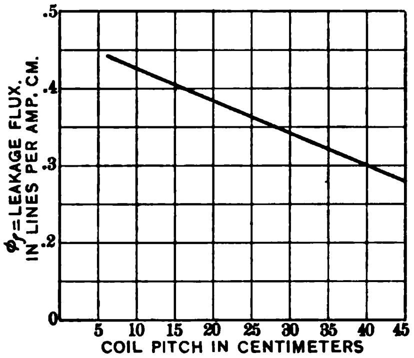

FIG. 18—END CONNECTION LEAKAGE

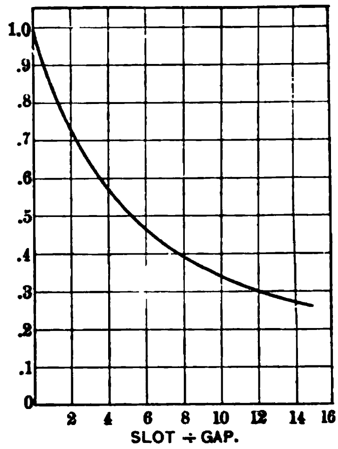

FIG. 19—" CARTER " FRINGING COEFFICIENT

The angle between I_0 and I_1 is $(90° - \psi)$ so that

$$\underset{\cdot}{I_0} = I_0 \cos(90° - \psi) - j\, I_0 \sin(90° - \psi) = I_0 \sin\psi - j\, I_0 \cos\psi \qquad (44)$$

The total stator current taken vectorially is

$$\underset{\cdot}{I} = \underset{\cdot}{I_1} + \underset{\cdot}{I_2} + \underset{\cdot}{I_0} \qquad (45)$$

$$\underset{\cdot}{I} = [I_1 + I_2 \cos(\psi - \alpha) + I_0 \sin\psi] + j\,[I_2 \sin(\psi - \alpha) - I_0 \cos\psi] \qquad (46)$$

or

$$I = \sqrt{(I_1 + I_2 \cos(\psi - \alpha) + I_0 \sin\psi)^2 + (I_2 \sin(\psi - \alpha) - I_0 \cos\psi)^2} \qquad (47)$$

The angle between I and I_1 is given by

$$\gamma = \tan^{-1} \frac{I_2 \sin(\phi - \alpha) - I_0 \cos \phi}{I_1 + I_2 \cos(\phi - \alpha) + I_0 \sin \phi} \tag{48}$$

Knowing γ we may find

$$\delta = \phi - \gamma \tag{49}$$

Taking I as zero vector, we have

$$\underset{\cdot}{E_2} = E_2 \cos \delta + j\, E_2 \sin \delta \tag{50}$$

In phase with I is the stator resistance drop $E_5 = R_s\, I$, and leading I by 90 degrees is the stator inductive drop $X_s\, I$. Combining E_2, E_5 and E_4 we obtain the impressed voltage per phase:

$$\underset{\cdot}{E} = \underset{\cdot}{E_2} + \underset{\cdot}{E_5} + \underset{\cdot}{E_4} = E_2 \cos \delta + E_5 + j\, E_2 \sin \delta + E_4 \tag{51}$$

or

$$E = \sqrt{(E_2 \cos \delta + E_5)^2 + (E_2 \sin \delta + E_4)^2} \tag{52}$$

The power factor at the stator terminals is

$$P.F. = \cos\ \theta = \cos\ \tan^{-1} \frac{E_2 \sin \delta + E_4}{E_2 \cos \delta + E_5} \tag{53}$$

The kilovolt-ampere input is

$$KV\text{-}A. = \frac{n\, E\, I}{1000} \tag{54}$$

The kilowatts input is

$$KW. = \frac{n\, E\, I \cos \theta}{1000} \tag{55}$$

NOTES ON DETERMINATION OF STARTING CHARACTERISTICS WITH LAMINATED POLES

While the theory given above covers a more or less ideal case, the engineer using such equations should bear in mind that actual conditions must always be different from those of computation. For example, the assumption is made that the frequency of the currents in the rotor is the same as the line frequency. Undoubtedly the departure from a sinusoidal distribution of flux will cause the wave form of currents induced to depart considerably from that of a sine wave and there are introduced frequencies other than the fundamental. No tests have been made to determine this wave form, although undoubtedly the volts consumed by reactance must be greatly influenced by the value of this frequency.

Another source of error is the effect of the contact resistance between the bars and the rings, which may be a large percentage of the total resistance of the rotor circuit. It is quite conceivable to have bars in large machines carrying 5000 amperes in which the drop at a poorly made contact would be a considerable percentage of the total with this amount of current. To insure against having the large contact resistance, it might be advisable to solder the joint. However, due to the difficulties which would appear in case the rings were to be removed, this would scarcely be a satisfactory solution. Therefore the engineer should allow for this discrepancy in the same way that he would allow in induction motors for contact resistance between the rings and the rotor bars when they are bolted together. Fortunately, however, this contact resistance is in favor of obtaining a smaller current input for the same starting torque.

In case the construction is such as to permit of the bars passing through slots which are entirely closed at the tops, tests should be made to determine the reactance for different currents with this type of slot. If these bridges over the tops of the slots were in laminated portions, the value of the reactance would be considerably different than if the metal were solid, due to the fact that eddy currents would be produced in the latter, which would tend to reduce the reactance. It would be very difficult to compute the reactance of this part of the circuit by theoretical means.

If the poles be laminated and the field ring solid, the losses in the field ring could be determined experimentally by taking careful readings with and without the amortisseur winding on the rotor. The voltage induced in the field coils is a crude measure of the flux which enters the solid field ring. As the losses due to eddy currents in the solid field ring are dependent upon the flux which enters it, these losses would be the same for the same voltages induced in the field coils with and without the amortisseur winding. By observing, for a definite voltage induced in the field coils, the starting torque as well as the power input to the stator (from which latter the stator losses may be deducted), the fraction of the total rotor loss which appears in the solid portions can be experimentally determined. From these tests the proportions of rotor losses in other machines could be predicted.

It is important to know the percentage of the leakage flux from pole to pole, or the equivalent, the difference between the flux which enters the head of the pole and that which enters the field ring. This can be determined experimentally by noting the voltage induced in exploring coils placed at various radial positions along the poles. The leakage factor σ is the ratio of the voltage per turn induced at the pole head to that induced at the pole base.

The phase difference between the eddy currents in the solid portions and the electromotive forces which produce them could in all probability be determined by means of a transformer, the secondary and core of which is solid metal, cast iron or steel as desired. By observing the power, volts and amperes input to the primary, and allowing for primary leakages and losses, the angle between the eddy currents and their voltages could be calculated.

If the short-circuiting rings are placed near the iron, the large currents in them may produce leakage fluxes which will later set up counter electromotive forces of considerable magnitude. If the rings are far removed from any iron, in general, it is believed that these leakage fluxes will not have very great influence. However, the writer has made no experimental determination of this, but believes that it would be desirable to cause alternating and direct currents to flow through the short-circuiting rings and measure the drop in each case. The curve given for determination of the stator end connection leakage was obtained from induction motors and includes the end ring leakage as well as the leakage around the end connections in the stator. In the same way the calculations obtained by means of this curve, used in conjunction with a synchronous motor, should include the end ring leakage as well as that of the stator end connections.

COMPARISON BETWEEN INDUCTION MOTORS AND SYNCHRONOUS MOTORS AT STARTING

The synchronous motor has frequently been compared with the squirrel cage induction motor in regard to the better conditions which obtain in the latter at the instant of starting. It has generally been believed that the poor starting conditions which exist in synchronous motors are due to the large air gap and the fact that only a portion of the stator periphery is covered by the rotor iron. Without doubt these two factors influence the current which is required to produce a definite starting torque. However, after careful observation it is believed by the writer that the leakage reactances in stator and rotor and the rotor resistance have far more influence upon the volt-ampere input at starting than the air gap and rotor configuration. The air gap, in general, influences the volt-ampere input from 10 to 20 per cent, whereas the leakage fluxes are the chief causes of the low power factor which obtains. Moreover, the increase in zigzag leakage due to the reduction in air gap may, in some motors, offset the decrease in volt-ampere input by reduction in magnetizing current. Furthermore there will be less uniformity of torque in the various rotor positions with a small air gap than with a large air gap. In the writer's judgment it is not good practise to sacrifice performance by reducing the air gap with a view of improving conditions at starting.

It is well known that to make satisfactory induction motors which will have leakage fluxes that will consume not more than 30 per cent of the impressed voltage when normal current flows, it is essential to use a large number of small slots in both stator and rotor. On the other hand, in synchronous motors it is general practise to use a small number of large slots. If we were to proportion the slots of the synchronous motor in the same manner in which induction motor slots are proportioned and cause the drop due to resistance in the rotor circuit to be equal or greater than that due to leakage fields, the power factor and other characteristics at starting would then compare very favorably with those of squirrel cage induction motors of the same speed and horse power.

CONCLUSION

As far as he knows, the writer is the first to have attempted an analysis of the relations of the various quantities which obtain while starting synchronous motors. In considering a phenomenon so complicated, it is possible that some of the statements which he has made may be incorrect and that some simpler and more accurate methods may be found by others for predicting the power and volt-ampere input during the starting period. The writer would therefore welcome any comments or criticisms which may be of future use in further investigations on this subject.

APPENDIX

I. REACTANCE OF A ROUND SLOT

The area included in Fig. 20 between the bottom of the slot and height $x = F = 2\left(\pi r \frac{2\alpha}{2\pi}\right) - (r \sin\alpha)(r\cos\alpha)$

$$= r^2\left(\alpha - \tfrac{1}{2}\sin 2\alpha\right) \qquad (56)$$

Taking unit length of slot and one ampere per conductor, flux in small area $dx = 0.4\pi\left(\frac{F}{\pi r^2}a\right)\frac{dx}{2y} = d\phi$ where a = number of conductors per slot.

But $x = r - r\cos\alpha$. Hence $dx = r\sin\alpha\, d\alpha$. Also $y = r\sin\alpha$ and

$$d\phi = 0.4\pi\left(\frac{Fa}{\pi r^2}\right)\frac{r\sin\alpha\, d\alpha}{2r\sin\alpha} = \frac{0.4\pi}{2}\left(\frac{Fa}{\pi r^2}\right)d\alpha$$

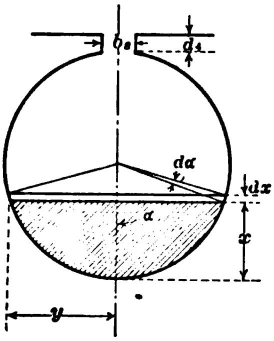

FIG. 20

The interlinkages per ampere will then be $\int_{\alpha=0}^{\alpha=\pi}\left(\frac{F}{\pi r^2}a\right)d\phi$

L in henrys =

$$\frac{1}{10^8}\int_{\alpha=0}^{\alpha=\pi}\left(\frac{F}{\pi r^2}a\right)^2\frac{0.4\pi}{2}d\alpha = \frac{0.4\pi}{2\times 10^8}\int_{\alpha=0}^{\alpha=\pi}\frac{r^4\left(\alpha-\frac{1}{2}\sin 2\alpha\right)^2 a^2\, d\alpha}{\pi^2 r^4}$$

$$= \frac{0.4\pi a^2}{2\pi^2\times 10^8}\left[\frac{\alpha^3}{3} + \frac{1}{4}\left(\frac{\alpha}{2} - \frac{1}{8}\sin 4\alpha\right) - \left(\frac{1}{4}\sin 2\alpha - \frac{\alpha}{2}\cos 2\alpha\right)\right]_0^\pi$$

$$= \frac{0.4\pi a^2}{2\pi^2\times 10^8}\left[\frac{\pi^3}{3} + \frac{\pi}{8} + \frac{\pi}{2}\right] = \frac{0.62\times 0.4\pi a^2}{10^8} \qquad (57)$$

If inches be used this becomes

$$L = \frac{0.62 \times 3.19\, a^2}{10^8} \tag{58}$$

The reactance per slot, allowing for leakage across opening at top, the depth of which is d_4 and width b_s, and expressed in henrys, is

$$X_b = \frac{2\,\pi \sim \lambda_b\, 0.4\,\pi}{10^8}\left(0.62 + \frac{d_4}{b_s}\right) a^2 \tag{59}$$

II. REACTANCE OF STATOR SLOTS WITH ALLOWANCE FOR SHORT PITCH

Consider unit length of slot and one ampere per conductor.

Let a = number of conductors per slot.

Consider, first, leakage reactance of coil B in Fig. 21.

The following is intended to apply when the currents in A and B are not in phase with each other.

ϕ_1 = flux due to B in lower portion of slot, linking with B.

ϕ_2 = flux due to B crossing slot above B.

ϕ_3 = flux due to A, threading A, but cutting B.

ϕ_4 = flux due to A, above A, and cutting B.

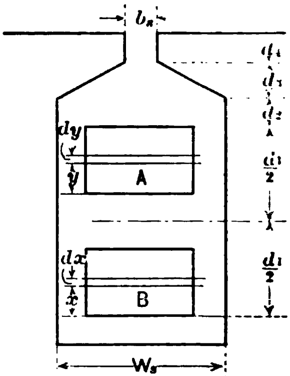

FIG. 21

1. $$d\,\phi_1 = \frac{x}{\frac{d_1}{2}}\,\frac{a}{2} \times 0.4\,\pi\,\frac{dx}{W_s}$$

$$\text{Interlinkages} = \int_0^{\frac{d_1}{2}} \frac{x}{\frac{d_1}{2}}\,\frac{a}{2}\, d\,\phi_1 = \frac{0.4\pi a^2}{W_s d_1^2}\int_{x=0}^{x=\frac{d_1}{2}} x^2\, dx = \frac{0.4\,\pi\, d_1 a^2}{24\, W_s} \tag{60}$$

2. $$\phi_2 = 0.4\,\pi\,\frac{a}{2}\left(\frac{d_1}{2\,W_s} + \frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)$$

$$\text{Interlinkages} = \frac{0.4\,\pi\, a^2}{4}\left(\frac{d_1}{2\,W_s} + \frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W}\right) \tag{61}$$

3.

$$d\phi_3 = \frac{0.4\,\pi\,a}{W_s 2}\,\frac{y\,d\,y}{\frac{d_1}{2}} \text{ and } \phi_3 = \frac{0.4\,\pi\,a}{W_s d_1}\int_{y=0}^{y=\frac{d_1}{2}} y\,d\,y = \frac{0.4\,\pi\,a\,d_1}{W_s 8}$$

$$\text{Interlinkages with } B = \frac{0.4\,\pi\,d_1\,a^2}{16\,W_s}\cos\omega \tag{62}$$

where ω = angle between currents in A and B

$$4.\quad \phi_4 = \frac{0.4\,\pi\,a}{2}\left(\frac{d_2}{W_s} + \frac{d_4}{W_s} + \frac{2\,d_3}{b_s + W_s}\right)$$

Interlinkages with B

$$= 0.4\,\pi\,\frac{a^2}{4}\left(\frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)\cos\omega \tag{63}$$

For three-phase with six-phase winding and for a pitch between $\frac{2}{3}$ and full pitch, $\omega = 60°$ and $\cos\omega = \frac{1}{2}$

Total interlinkages for B, three-phase = (60) + (61) + (62) + (63)

$$= 0.4\,\pi\,a^2\left[\frac{19}{96}\,\frac{d_1}{W_s} + \frac{3}{8}\left(\frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)\right] \tag{64}$$

For two-phase we obtain, allowing for $\omega = 90^0$ and $\cos\omega = 0$,

$$0.4\,\pi\,a^2\left[\frac{1}{6}\,\frac{d_1}{W_s} + \frac{1}{4}\left(\frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)\right] \tag{65}$$

Now consider coil A when there is a phase difference between currents in A and B.

ϕ_2 = flux due to B, linking with A.
ϕ_3 = flux due to A, threading A and linking with A.
ϕ_4 = flux due to A, above A, linking with A.

$$1.\quad \phi_2 = \frac{0.4\,\pi\,a}{2}\left(\frac{d_1}{2\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right) \tag{66}$$

Interlinkages

$$= \frac{0.4\,\pi\,a^2}{4}\left(\frac{d_1{}^*}{4\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_4} + \frac{d_4}{b_s}\right)\cos\omega \quad (67)$$

2. $$d\,\phi_2 = \frac{0.4\,\pi}{W_s}\;\frac{y}{\frac{d_1}{2}}\;\frac{a}{2}\,dy$$

$$\text{Interlinkages} = \int\left(\frac{a}{2}\;\frac{y}{\frac{d_1}{2}}\right)d\,\phi_2 = \frac{0.4\,\pi a^2}{W_s\,d_1{}^2}\int_{y=0}^{y=\frac{d_1}{2}} y^2\,dy = \frac{0.4\,\pi}{24}\,\frac{a^2 d_1}{W_s} \quad (68)$$

3. $$\phi_4 = \frac{0.4\,\pi\,a}{2}\left(\frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right)$$

$$\text{Interlinkages} = \frac{0.4\,\pi\,a^2}{4}\left(\frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right) \quad (69)$$

Total linkages for A for three-phase

$$= 0.4\,\pi\,a^2\left[\frac{7}{96}\;\frac{d_1}{W} + \frac{3}{8}\left(\frac{d_2}{W_s} + \frac{2\,d_3}{(b_s + W_s)} + \frac{d_4}{b_s}\right)\right] \quad (70)$$

For two-phase, interlinkages

$$= 0.4\,\pi\,a^2\left[\frac{1}{24}\;\frac{d_1}{W_s} + \frac{1}{4}\left(\frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right)\right] \quad (71)$$

When using short pitch, if we drop back by electrical angle $\beta = \omega$ the two coils in all slots will have currents differing in phase by angle ω. For any pitch between this and full pitch, there are $\frac{N_1}{2\,n}\,\beta\left(\frac{n}{180°}\right) - B$ coils per phase and $\frac{N_1}{2\,n}\,\beta\left(\frac{n}{180°}\right)$ A coils per phase, where N_1 = total number of stator slots and n = number of phases.

---

*The fact that this is $\frac{d_1}{4\,W_s}$ instead of $\frac{d_1}{2\,W_s}$ is because not all of the conductors in A are cut by ϕ_2 threading A. This brings in the average value. The result may also be proved by a simple integration.

In addition there are $\frac{N_1}{n}\left(1 - \frac{\beta n}{180°}\right)$ slots per phase in which the currents in the two coils are in phase with each other, and for which the interlinkages are:

$$0.4\pi a^2\left(\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right) \qquad (72)$$

For a three-phase winding the total interlinkages per phase are, from equations (64), (70) and (72):

$$0.4\,\pi\,a^2 \left\{\left[\frac{19}{96}\frac{d_1}{W_s} + \frac{3}{8}\left(\frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)\right]\frac{N_1}{2\,n}\,\frac{\beta}{60°}\right.$$

$$+\left[\frac{7}{96}\frac{d_1}{W_s} + \frac{3}{8}\left(\frac{d_2}{W_s} + \frac{d_4}{b_s} + \frac{2\,d_3}{b_s + W_s}\right)\right]\frac{N_1}{2\,n}\,\frac{\beta}{60°}$$

$$\left.+\left[\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right]\frac{N_1}{n}\left(1 - \frac{\beta}{60°}\right)\right\}$$

After reduction this becomes:

$$\frac{0.4\,\pi\,a^2\,N_1}{n}\left\{\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right.$$

$$\left.-\ \frac{\beta}{60°}\left[0.198\,\frac{d_1}{W_s} + \frac{5}{8}\left(\frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right)\right]\right\}$$

If we allow an approximation of $0.208\,\frac{d_1}{W_s} = \frac{1}{3} \times \frac{5}{8}\,\frac{d_1}{W_s}$ instead of $0.198\,\frac{d_1}{W_s}$, we obtain for three-phase:

$$\frac{0.4\,\pi\,a^2\,N_1}{3}\left\{\left[1 - \frac{5}{8}\left(\frac{\beta}{60°}\right)\right]\left[\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right]\right\} \qquad (73)$$

And for two-phase, we may similarly derive, allowing also a slight approximation:

$$\frac{0.4\,\pi\,a^2\,N_1}{2}\left[1 - \frac{3}{4}\left(\frac{\beta}{90°}\right)\right]\left[\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right] \qquad (74)$$

The slot reactance for three-phase is

$$X_{s_1} = \frac{2\,\pi \sim \lambda_s\, p\, S\, 0.4\,\pi\, a^2}{10^8}\left[\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right]\left(1 - \frac{5}{8}\,\frac{\beta}{60^\circ}\right) \qquad (75)$$

And for two-phase

$$X_{s_1} = \frac{2\,\pi \sim \lambda_s\, p\, S\, 0.4\,\pi\, a^2}{10^8}\left[\frac{d_1}{3\,W_s} + \frac{d_2}{W_s} + \frac{2\,d_3}{b_s + W_s} + \frac{d_4}{b_s}\right]\left[1 - \frac{3}{4}\,\frac{\beta}{90^\circ}\right] \qquad (76)$$

III. END CONNECTION REACTANCE

Let us first assume that there is one coil per slot. There are then $S\,a$ conductors per pole per phase in each "phase bundle" representing a group of conductors, and there are $\frac{p}{2}$ groups per phase. If ϕ_f represent the flux per inch of free length with one conductor per group and one ampere per conductor, and the length of end connections per coil be $(M.T. - 2\,\lambda_s)$ where $M.T.$ = mean length of turn and λ_s = gross length of iron, we have for the end connection inductance

$$L_f = \frac{\phi_f\,(S\,a)^2\,p}{10^8 \times 2}\,(M.T. - 2\,\lambda_s) \qquad (77)$$

And the end connection reactance $= X_f = 2\,\pi \sim L_f$

$$X_f = \frac{(S\,a)^2\,p\,\pi \sim \phi_0}{10^8}\,(M.T. - 2\,\lambda_s) \qquad (78)$$

It has been found that the end connection reactance is nearly the same for single-layer as for two-layer windings, if the mean turn and other quantities be the same. We are justified, therefore, in using the above equation for two-layer windings as well as single-layer. The values of ϕ_f may be obtained from Fig. 18.

IV. Zigzag Reactance

At the instant of starting, leakage lines of force emerge from the stator teeth, cross the air gap, enter the rotor poles and return to an adjacent stator tooth without interlinking with any rotor conductor. Similarly, leakage flux emerges from the rotor without cutting the stator conductors. This flux has been given the name of zigzag leakage and is well known to induction motor designers.

Modifying the results obtained by C. A. Adams* to suit our notation, we obtain

$$\phi_s = \frac{0.84\,\lambda}{\Delta}\left[\frac{(W_t + C_1\,W_s) + (W_{t_2} + C_2\,W_{s_2})}{2\,\lambda} - \frac{1}{2}\right]^2 \quad (79)$$

In this ϕ_s is the leakage flux from tooth tips with one ampere per conductor in one slot per centimeter length; λ = average tooth pitch in the stator and rotor; Δ = single air gap in centimeters; W_t, W_{t_2}, W_s and W_{s_2} are respectively the tooth and slot widths for primary and secondary; C_1 and C_2 are the Carter coefficients for fringing from Fig. 19.

The inductance is

$$L_s = \frac{\phi_s\,a^2\,\lambda_s\,p\,S}{10^8}$$

$$= \frac{a^2\,\lambda_s\,p\,S \times 0.84\,\lambda}{10^8\quad\Delta}\left[\frac{(W_t + C\,W_s) + (W_{t_2} + C_2\,W_{s_2})}{2\,\lambda} - \frac{1}{2}\right]^2 \quad (80)$$

As $\left(\frac{W_{t_2} + C_2\,W_{s_2}}{\lambda_2}\right)$ is nearly equal to unity if the rotor slots be partly closed, (λ_2 being rotor slot pitch) we may write, after substituting 1 for this expression,

$$L_s = \frac{0.84\,\lambda\,a^2\,\lambda_s\,p\,S}{10^8\quad\Delta}\left[\frac{W_t + C_1\,W_s}{2\,\lambda}\right]^2$$

$$= \frac{0.21\,a^2\,\lambda_s\,p\,S}{10^8\,\Delta\lambda}\,(W_t + C_1\,W_s)^2 \quad (81)$$

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*See C. A. Adams: *Design of Induction Motors*, Transactions A.I.E.E., 1905, XXIV, page 665.

And the reactance =

$$X_s = \frac{0.21\, a^2\, \lambda_s\, p\, S\, 2\,\pi \sim}{10^8\, \Delta\, \lambda}\,(W_t + C_1\, W_s)^2$$

$$= \frac{1.32\, a^2\, \lambda_s\, p\, S \sim}{10^8\, \Delta\, \lambda}\,(W_t + C_1\, W_s)^2 \qquad (82)$$

If inches be used,

$$X_s = \frac{3.35\, a^2\, \lambda_s\, p\, S \sim}{10^8\, \Delta\, \lambda}\,(W_t + C_1\, W_s)^2 \qquad (83)$$

V. TOOTH TIP LEAKAGE

To distinguish that leakage flux which crosses the air gap when the pole is opposite the stator from the leakage around the teeth when they are situated between the poles, we shall call the former "zigzag" and the latter "tooth tip" leakage.

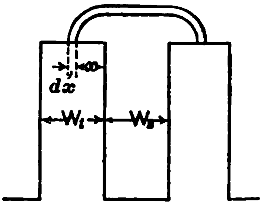


FIG. 22

We may derive an expression for the tooth tip leakage by assuming that this leakage flux travels in the arcs of circles and in straight lines. The leakage flux which encircles one slot in small distance dx (Fig. 22) is:

$$d\phi = \frac{(0.4\,\pi\, a)\, dx}{\pi\, x + W_s}$$

And the interlinkages =

$$\int a\, d\,\phi = 0.4\,\pi\, a^2 \int_{x=0}^{x=W_t} \frac{dx}{\pi\, x + W_s} = \frac{0.4\,\pi\, a^2}{\pi}\log_e \frac{(\pi\, W_t + W_s)}{W_s}$$

or

$$L_t = \frac{0.4\,\pi \times 2.3}{10^8\,\pi}\, a^2 \log_{10}\left(\frac{\pi\, W_t}{W_s} + 1\right) = 0.4\,\pi \times 0.73\, a^2 \log_{10}\left(\frac{\pi\, W_t}{W_s} + 1\right)$$

(84)

In order to allow for the shortening of lines and the large area through which the flux passes, it has been found from test that accurate results are obtained by increasing the factor 0.73 to unity.

The above applies to one slot per pole per phase. When there are two or more slots per pole per phase, it has been found from test to be satisfactory to obtain the tooth-tip leakage with two slots per pole per phase. Deriving this in the same manner as above for one slot per pole per phase, we obtain, after substituting 2 for 1.46 to allow for shortening of lines, etc., and adding expression in equation (84),

$$L_t = \frac{0.4\,\pi\,a^2}{10^8}\left[\log_{10}\left(1 + \frac{\pi\,W_t}{W_s}\right) + 2\log_{10}\left(1 + \frac{\pi\,W_t}{2\,W_s + W_t}\right)\right] \tag{85}$$

The tooth-tip reactance per phase is:

$$X_t = \frac{2\,\pi \sim 0.4\,\pi\,a^2\,\lambda_s\,p\,S}{10^8}\left[\log_{10}\left(1 + \frac{\pi\,W_t}{W_s}\right)\right.$$

$$\left. + 2\log_{10}\left(1 + \frac{\pi\,W_t}{2\,W_s + W_t}\right)\right] \tag{86}$$

Or $X_t = \dfrac{7.9 \sim a^2\,\lambda_s\,p\,S}{10^8}\left[\log_{10}\left(1 + \dfrac{\pi\,W_t}{W_s}\right)\right.$

$$\left. + 2\log_{10}\left(1 + \frac{\pi\,W_t}{2\,W_s + W_t}\right)\right] \tag{87}$$

VI. EFFECT OF SHORT PITCH UPON ZIGZAG AND TOOTH TIP LEAKAGE

It may be proved in the same manner as for slot reactance that the effect of fractional pitch of coils is to decrease the zigzag and tooth tip reactance by the factor $\left(1 - \dfrac{M,\beta\, n}{180^\circ}\right)$

The zigzag leakage is effective over those portions of the stator which have poles opposite them, whereas the tooth tip leakage appears between poles only. Hence, if u is the polar arc and τ' is the pole pitch at the inner periphery of the stator, the fraction of the stator to which the zigzag leakage applies is $\dfrac{u}{\tau'}$ and that over which the tooth tip leakage is effective is $\dfrac{\tau' - u}{\tau'}$

Hence, we may add these two leakage reactances and obtain after simplifying:

$$X_z + X_t = \frac{3.35\, a^2\, \lambda_s\, p\, S \sim}{10^8\, \tau'} \Bigg\{ \frac{u\,(W_t + C\, W_s)^2}{\Delta\, \lambda} +$$

$$2.36\,(\tau' - u) \Bigg[\log_{10}\bigg(1 + \frac{\pi\, W_t}{W_s}\bigg) + 2\log_{10}\bigg(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\bigg)\Bigg]\Bigg\}$$

$$\bigg\{1 - \frac{M\, \beta\, n}{180^\circ}\bigg\} \qquad (88)$$

The above applies when the metric system is used and when the number of slots per pole per phase is not less than two. For the inch system use 8.5 instead of 3.35; and for one slot per pole per phase, omit $2 \log_{10}\left(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\right)$

VII. COMBINATION OF EQUATIONS TO GIVE THE TOTAL STATOR REACTANCE

By adding the leakage fluxes in the various parts of the stator we have, for the metric system,

$$X_s = X_{s_1} + X_z + X_t + X_f =$$

$$\frac{7.9 \sim p\, a^2\, S\, \lambda_s}{10^8} \Bigg\{ \bigg(1 - \frac{M\, \beta\, n}{180^\circ}\bigg) \Bigg(\frac{d_1}{3\, W_s} + \frac{d_2}{W_s}$$

$$+ \frac{2\, d_3}{b_s + W_s} + \frac{d_4}{b_s} + \frac{0.425\, u\, (W_t + C\, W_s)^2}{\tau'\, \Delta\, \lambda}$$

$$+ \bigg(1 - \frac{u}{\tau'}\bigg) \Bigg[\log_{10}\bigg(1 + \frac{\pi\, W_t}{W_s} + 2\log_{10}\bigg(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\bigg)\Bigg]\Bigg)$$

$$+ 0.4\, S\, \phi_f \bigg(\frac{M.T.}{\lambda_s} - 2\bigg)\Bigg\} \qquad (89)$$

For the inch system of units use 20 instead of 7.9 and express ϕ_f in lines per ampere-*centimeter*.

VIII. SINGLE-PHASE REACTANCE

If single-phase current be caused to flow in one leg of the stator winding of a two- or three-phase machine, and the stator be provided with short pitch winding, then there will be some slots in which the currents in both coils will flow in the same direction, and other slots in which the current flows in only of two coils. By proceeding with a method similar to that given for polyphase machines with polyphase currents, we obtain a result similar to equation (76):

$$X_{s_1} = \frac{2\,\pi \sim \lambda_s\, p\, S\, 0.4\, \pi\, a^2}{10^8} \left[\frac{d_1}{3\, W_s} + \frac{d_2}{W_s} + \frac{2\, d_3}{W_s + b_s} + \frac{d_4}{b_s} \right] \left[1 - \frac{3}{4}\, \frac{\beta\, n}{180^\circ} \right] \qquad (90)$$

This holds for either two- or three-phase, a four-phase winding being used for the former and a six-phase winding for the latter.

To obtain the total reactance with single-phase current in one phase only of a polyphase stator, the rotor being removed, we must allow for the tooth tip and end connection leakages, the derivations of which are given in this appendix, and obtain, with the metric system:

$$X_s = \frac{7.9 \sim p\, a^2\, S\, \lambda_s}{10^8} \left\{ \left(1 - \frac{3}{4}\, \frac{\beta\, n}{180^\circ}\right) \left[\frac{d_1}{3\, W_s} + \frac{d_2}{W_s} + \frac{2\, d_3}{b_s + W_s} + \frac{d_4}{b_s} + \log_{10}\left(1 + \frac{\pi\, W_t}{W_s}\right) + 2 \log_{10}\left(1 + \frac{\pi\, W_t}{2\, W_s + W_t}\right) \right] + 0.4\, S\, \phi_f \left(\frac{M.T.}{\lambda_s} - 2 \right) \right\} \qquad (91)$$

If inches be used, substitute 20 for 7.9 and express ϕ_f in lines per ampere-centimeter.

DISCUSSION ON "SELF-STARTING SYNCHRONOUS MOTORS" (FECHHEIMER). PITTSBURGH, PA., APRIL 25, 1912.

R. B. Williamson: Mr. Fechheimer's paper presents a large amount of interesting and valuable experimental data regarding a type of motor that is rapidly coming into use, and about which comparatively little has been published.

The self-starting synchronous motor, when started with the exciting field open-circuited, is essentially a squirrel-cage induction motor for the time being, although it is a more or less imperfect one. In general, all the tests given by the author point to the conclusion that the same rules laid down for the design of induction motors to secure the maximum starting torque with minimum line current, must also be observed in the design of a self-starting synchronous motor. For example, the reactances of both stator and rotor windings must be kept down as much as possible, and this in turn affects the number and proportions of stator and rotor slots. The squirrel-cage winding must be designed with sufficient resistance to give the required starting torque, and the rotor bars must be spaced to avoid dead points as far as possible. This last point is very important. It is of little use to make elaborate calculations and go into refinements of design to obtain a squirrel cage which will produce a given *average* torque if the arrangement of bars is such that the *minimum* torque is insufficient to start the machine. The author has very properly called attention to this point. It is true that some of the requirements for a good induction motor cannot well be met in the synchronous motor, but the nearer the induction motor design can be approached, the better, at least so far as starting is concerned. The large air gap and discontinuous rotor surface are desirable for the synchronous motor. So far as starting torque is concerned, the large air gap is not a great disadvantage; an induction motor may have a relatively large gap and yet be quite satisfactory so far as starting characteristics are concerned. It is true that the larger the gap, the larger will be the component of line current required for setting up the flux across the gap, and to this extent the total line current will be increased.

A point to be noted regarding the squirrel-cage winding of a self-starting synchronous motor is that it is in use only during the starting period, except possibly for momentary or periodic currents that may flow in it if hunting takes place. The squirrel cage can therefore be designed with reference to the starting conditions rather than operating conditions. On the other hand, in a regular induction motor, working currents flow in the squirrel cage and the loss at starting must necessarily be limited in order to secure a satisfactory efficiency while the motor is running under regular load.

In designing the squirrel cage for a synchronous motor, the service for which the motor is to be used should be kept in mind. For starting air compressors (unloaded), motor-generators or similar service, the torque required to overcome static friction is relatively high, but drops off rapidly as soon as the machine starts. At or near synchronism, the driving torque required is relatively small. For such service, a high-resistance squirrel cage is desirable, as it will develop a high torque at starting, and will allow the motor to come nearly up to synchronism on a half-voltage tap, on account of the light running load. There will not, therefore, be an excessive rush in current when the motor is thrown over to full line voltage. On the other hand, a motor used for starting, say, a centrifugal pump or fan, where the torque required to overcome static friction is not large, while the running torque near synchronism may be very high, requires a low-resistance squirrel cage in order to approach closely to synchronism before full line voltage is thrown on. It has been found that in case a motor is brought into synchronism on the low-voltage tap by the application of direct current in the fields, it sometimes happens that when the motor is thrown over to full voltage, an excessive rush of current that may trip the circuit-breakers takes place. This can be avoided by increasing the field excitation to quite a large amount just before the switch is thrown over, thus increasing the counter e.m.f. of the motor. In case this is done, sufficient time must be allowed for the field current to increase to the required amount before throwing over to line voltage.

Mr. Fechheimer has called our attention to the falling off in torque near synchronism, and mentioned that the application of a small direct-current excitation will help the motor to pull in. The writer noted this effect some time ago, but the present paper is the first place where he has seen it pointed out that there is in each case a critical value for this excitation giving the best results. The curves shown in Fig. 11 are particularly interesting in this connection.

In applying direct-current excitation, care must be taken that it is not done when the machine is much below synchronism. Cases have occurred where this resulted in an insulation breakdown of the exciter armature, on account of the high induced voltage in the field of the synchronous motor when running with a large slip.

It is a well-known fact that synchronous motors, when started with the field circuit closed, frequently tend to stick at half speed. This, however, can hardly be attributed to higher harmonics in the wave form of the motor. For such to be the case, the harmonics would be of an even order, whereas even harmonics do not exist in a symmetrical wave. It seems that the phenomenon of running at half speed might be explained as follows: If an alternator of frequency *n* cycles per second is excited with direct current, it must be driven at synchronous speed to generate this frequency. If, on the other hand, it is excited with alternating current at frequency n instead of direct current, and at the same time driven at synchronous speed, it will generate an e.m.f. having double frequency $2n$. Or, if it is driven at one-half synchronous speed and excited with alternating current of frequency $\frac{1}{2}n$, it will generate normal frequency n. Now, if the latter case is reversed, and the generator operated as a synchronous motor at line frequency n, and if at the same time its fields are excited with alternating current at frequency $\frac{1}{2}n$, the motor will run at one-half synchronous speed. When a synchronous motor is started with its fields closed and attains one-half speed, the frequency of the current in the closed rotor circuit is $\frac{1}{2}n$, and the effect is the same as if the motor were excited from an external source at one-half frequency. The motor, therefore, tends to lock into step and will so continue running unless the conditions are such that the torque due to the squirrel cage exceeds the pull-out torque of the synchronous motor when operating in this manner. When the field circuit is opened, the half-frequency exciting current disappears and the squirrel-cage torque brings the motor nearly to synchronism.

Regarding the high e.m.f. induced in the fields at starting, particularly those wound for 250-volt excitation, this can usually be taken care of by extra insulation on the coils and collector rings. It should be remembered, however, that the same precautions regarding insulation should also be taken in connection with the wiring for supplying the exciting current. Mention has been made of the effect of solid poles in reducing the voltage generated in the field. Laminated poles without dampers or squirrel-cage winding undoubtedly permit a high induced voltage, but this is very greatly reduced in machines provided with a squirrel cage, so that the solid pole has little advantage in this respect. In one case with which the writer is familiar, the addition of dampers reduced the induced voltage to approximately 25 per cent of its former voltage.

The analytical discussion is of value in that it shows the relative importance of the various quantities entering into the determination of a given torque and the corresponding line current, power factor, etc., during the starting period. However, the whole subject is complex, and so many assumptions have to be made on which to base calculations, that the engineer must place reliance on tests more than anything else.

F. D. Newbury: The Institute is to be congratulated on having a paper of this quality on a design subject. We do not often get them. This is a very complicated subject. The synchronous motor is such a rapid-change artist during starting, starting as an induction motor, sometimes changing to a synchronous motor at half speed, and sometimes not changing until it gets pretty near the full speed, that the conditions are quite complex. I will not attempt any general discussion of Mr. Fechheimer's paper, but I do want to call attention to one or two points.

The " non-uniformity of torque at the instant of starting," and the " unbalance in phases," I have noticed are very much larger without amortisseur windings or without continuous end rings, when there are damper windings upon the individual poles. I do not believe Mr. Fechheimer mentions whether the motors he tested had continuous end rings or not.

In connection with the field circuit at starting, with an open field circuit, as Mr. Fechheimer points out, there is a large voltage induced in the field windings, particularly with the higher exciting voltages. He also points out that there is considerable decrease in starting torque with the field short-circuited, but the curves also show that with some resistance in the field circuit this decrease in torque is practically nil. I think it is, therefore, preferable to start the motors with the field circuit closed, and through as much resistance as is ordinarily placed in the field rheostat. This reduces, in fact, eliminates, the danger of any insulation strains in the field circuit, and does not cause any great decrease in starting torque.

Mr. Fechheimer devotes one section to the subject of " driving of fans and pumps." I am familiar with a motor of about 200 kv-a. at 500 rev. per min. on 25 cycles, which is arranged to drive a fan in which the starting conditions are very severe. The motor must be placed on the line with about 80 per cent of full load torque, at the instant of falling into step, with not more than 2.5 normal kv-a. from the line. I think that is about as good as a corresponding induction motor could do, which also bears out well the contention which has been made, that there is not a great deal of difference between a properly designed synchronous motor and a corresponding induction motor.

I agree with Mr. Fechheimer, that in obtaining good starting conditions, the distribution of slots in the rotor and in the stator is important and that it is not good engineering to decrease the air gap in order to get a little better starting conditions. The decrease of air gap of course results in much smaller pull-out as a synchronous motor, and the pull-out as a synchronous motor is undoubtedly much more important than the slightly smaller starting current.

Mr. Fechheimer has devoted most of his paper to the conditions of actual starting. There is an equally interesting field for discussion—the conditions after the motor is connected to the low voltage, and the starting operation is completed by connecting to the line voltage and exciting the field.

As Mr. Williamson pointed out, the complete starting conditions are improved with an increased field current. The armature current on low voltage may be considerably higher than it would be with lower field current, but in throwing over to line voltage there is not an excessive rush of current which will open the current breakers.

H. M. Gassman: The mention of induced voltage in the fields of synchronous motors recalls some comparative tests I made on synchronous motors with 250-volt windings. The motors were of 250 kv-a. capacity and the voltage was measured at the field switch on the switchboard. In both cases approximately one-half normal voltage was applied for starting the motors.

The solid-pole motor gave as a maximum 1500 volts induced in the field at starting. The motor with laminated poles and copper end rings showed an induced voltage of 4000. Such induced voltage deserves consideration on account of the danger to which the operator is exposed when starting synchronous motors, and the chance of such induced voltage breaking down the ordinary insulation used on the complete field circuit and even breaking down the rotor insulation after it has deteriorated from use or exposure. The rotors in this case were designed to withstand 5000 volts when new, which leaves a very small factor of safety for deterioration when the induced voltage is so high.

When the ammeter of the synchronous motor is not short-circuited in starting, it is an advantage to insert the resistance in the field, as suggested by Mr. Fechheimer, for the purpose of reducing the chances of damaging the ammeter needle. Damage to the needle might be avoided by selecting an instrument with larger capacity and also by an increase in the size of the current transformer. This, however, is not desirable, on account of the performance of wattmeters and the indicating meters on light loads.

A. M. Dudley: One point in Mr. Fechheimer's abstract of his paper must be taken with certain modifications and also brings out the need for correction in one of our existing Standardization Rules. I understand that such correction is contemplated in connection with the revision now under way. I refer to Mr. Fechheimer's statement that the real watts input into the rotor is a fair measure of the starting torque. This statement is reasonably correct, but he said, in addition, that if the real watts input into the primary at standstill were measured, and the loss in primary copper were subtracted therefrom, the remainder would reasonably represent the input into the rotor which reappears directly as starting torque. It is well known at the present time that there are certain losses at standstill due to eddy currents in different parts of the machine, which do not appear as starting torque and which are not present as losses when the machine is running at normal full load speed. For this reason the starting torque, as figured in this manner from the locked kilowatts input, is usually higher than the machine actually develops, and the secondary copper loss as so figured is too high, showing an efficiency at full load speed which is less than is actually the case. This discrepancy is not always so small as to be negligible and in extreme cases a starting torque of 1.7 times full load torque may be indicated from the locked kilowatts and the machine may actually test out only 1.2 times.

Referring to the Standardization Rules on this point, under Section 167, they definitely state that the locked watts when the full load primary energy current is flowing in the windings are directly chargeable against the motors either as copper losses in the primary and secondary or as so-called load losses. This, I believe, we all recognize as incorrect and the rules could be modified so as to correct this inaccuracy.

W. J. Foster: I would like to say a word with reference to the solid pole versus the laminated pole. I agree that it is not permissible to have such high induced potential as mentioned in a particular case by a previous speaker. Of course, in the designing of the synchronous motor we must strike a compromise. There are a good many conflicting factors, and we must combine them so as to obtain a motor that is practicable.

Now in the case mentioned of the motor with solid poles, undoubtedly the reduction of the induced voltage, due to the solid pole, is a good thing, when you consider the danger of the induced potential. We ought not to allow a synchronous motor to be built that is absolutely open-circuited and with laminated poles and nothing to keep down the induced potential. In the particular motor that the speaker had in mind as subject to criticism, probably the squirrel-cage winding, there is very high resistance. There has been that danger in the past. Many motors have been built with altogether too high a resistance. Such a motor shows up well in the initial start, since it keeps down the amount of current taken from the line, and if the question is asked as to the current required to start, the answer is made so as to apply at the instant of starting. Hence there is the temptation to make that very low, say, full load current or less than full load current. This proportioning of squirrel-cage windings does not, it seems to me, result in a machine which is a practicable one—either the windings should have much lower resistance, or, what is simpler, short-circuiting collars should be put on the poles, as they will cut down the induced potential. I recall some experiences in the matter of short-circuiting collars. There is danger of getting too low resistance, so that there will be trouble at the half-speed point in starting up. There is danger, if alloys are called for, on account of the uncertain character of what one gets from the foundry. You sometimes get material with 50 per cent higher resistance than at other times.

In general, it is better to design the squirrel-cage windings with lower resistance, or with that which it needs as it approaches synchronism.

I agree with the emphasis laid by the author on the desirability of providing definite paths for the current in the starting winding. It seems to me more scientific and approaches more nearly the induction motor design. The synchronous motor is at a disadvantage when compared with the induction motor, since no serious attempt has been made to develop synchronous motors as a class of machines by themselves. Most commercial synchronous motors are generators adapted to the use as motors.

The author brought out a number of points with which I agree.

As to the matter of air gap—when you consider all the characteristics of a good motor, I think the gap of a synchronous motor should be approximately the same as of a generator.

I would like to ask Mr. Fechheimer, in closing, if he is ready to make a statement with reference to the ratio of slots, the region within which he considers good practise to lie? Mr. Fechheimer has warned us in both directions, against the multiple and against the prime relation; this helps a good deal, but I should like him to make a positive statement. I think we are all greatly indebted to Mr. Fechheimer for the paper, which is an excellent treatise on the subject.

B. G. Lamme: Considering the synchronous motor problem as a whole, it has been known for many years that, in starting and accelerating such a machine, it is an induction motor until it comes up to synchronism, and that, while acting as an induction motor, it followed the laws of the induction motor; or rather that it followed these laws as closely as the crudeness of the construction would permit, for the synchronous motor is naturally an imperfect form of induction motor. It has been known for a long time that the starting torque of the synchronous motor varies as the square of the impressed voltage, which is a well-known law of the induction motor. The same is true of many other relationships which Mr. Fechheimer has brought out, and the great value of his paper lies in the fact that he has shown how very closely the synchronous motor follows the same laws as the induction motor, when its imperfect construction as an induction motor is taken into account.

One of the first things which we teach designers of induction motors is that, to obtain full load torque at the start, there must be an expenditure of at least full load energy in the secondary circuit. Mr. Fechheimer shows that in the synchronous motor we get practically the same result in spite of the fact that the field structure of the synchronous motor, which becomes the secondary of the machine as an induction motor, is, magnetically, badly proportioned, compared with the usual secondary construction of the normal induction motor. At half speed the synchronous motor tends to hesitate, one might say, or to drop into a sub-synchronous speed. In this feature it also follows the principles of the induction motor, which, with a wound secondary, will tend to run at half speed when its secondary has only one circuit or phase closed on itself, and will even pull a considerable load. The synchronous motor at half speed represents a similar condition to a certain extent. The secondary conditions, represented by the polar arrangement of the magnetic circuit and the field coils of the synchronous motor, tend to give, to a certain extent, a single-phase condition in the secondary. In particular, the field winding, closed on itself, tends to give the effect of a single secondary circuit, and therefore tends to lock the machine at half speed. This action is neutralized, to a certain extent, by any polyphase actions in the secondary circuit, and the greater the polyphase tendency compared with the single-phase, the less difficulty there is in carrying the machine past the half-speed point. If the single-phase action of the secondary preponderates, the motor may have a strong tendency to lock at half speed.

When the motor speeds up, it approaches as near synchronism as the resistance of the secondary winding will allow. With a very low-resistance secondary winding, a very close approach to synchronism is attained, as in the induction motor, and it is easier to pull the machine into step. The higher the resistance of the secondary, and therefore the better the starting conditions, the greater will be the " slip " at full speed, and therefore the harder will it be to pull the motor into synchronism. It is difficult to "see" just what is going on in the motor at the instant it pulls into synchronism, but the conditions can be approximated by considering the synchronous motor at standstill with its terminals connected to an alternating-current generator which is started from rest, the fields of both the generator and motor being excited by direct current. At the first instant of movement of the generator, there can be no current between the machines, because there is no electromotive force generated until the generator gets into motion. A certain low speed is required to generate enough e.m.f. to overcome the resistance of the armature windings of the two machines. At one per cent of normal speed there may be sufficient current flowing between the machines to exert a considerable torque, but the motor is at standstill while the generator is rotating at one per cent of normal speed. Observing the rotor of the synchronous machine under this condition, it will be seen to quiver or oscillate back and forth a few times, and then jerk or swing itself into step. Sometimes there is simply a small quiver and then a sudden jerk into synchronism with the generator. At other times, there may be a very pronounced oscillation or swing of the synchronous motor, and finally it swings itself to such an angle that it naturally falls into step. It is obvious that the nearer the generator can be to zero speed when this action occurs, the easier it will be to pull the synchronous motor into step. Watching a motor start under these conditions gives a very good impression of what happens under ordinary conditions of synchronizing when the generator is running at normal speed.

In one important feature the synchronous motor is quite different from the induction motor. In the synchronous motor, in order to get a good pull-out torque, usually the direct-current field magnetomotive force must be high compared with the armature magnetomotive force. Ordinarily, the field ampere-turns in the synchronous motor will be about one and one-half times as great as the effective armature ampere-turns at full load, in order that the motor may be able to develop a maximum of about two times full load torque. This high field strength is necessary in order to give the proper overload torque. On the other hand, in the induction motor the magnetizing ampere-turns are possibly only 30 per cent of the full load ampere-turns; that is, in the induction motor, the exciting ampere-turns are only about 20 per cent as great as in the synchronous motor. Herein is one prominent difference between the two types, and in this lies the difficulty in making a machine which will be both a good synchronous motor and a good induction motor. If the induction motor requires only 30 per cent of full load ampere-turns to excite its field, then as a synchronous motor it would still require only an excitation corresponding to 30 per cent of the armature ampere-turns, whereas, in fact, it should have about one and one-half times the armature ampere-turns for excitation, as stated before. With 30 per cent excitation, it would have a pull-out torque of possibly 40 per cent of full load torque, as a synchronous machine, which is an impracticable condition. In order to get two times full load torque it would require an excitation of one and one-half times the ampere-turns of the armature, as stated before, and when acting as an induction motor the same excitation would be required. This would therefore lead to an induction motor having a magnetizing current of one and one-half times the value of the work current, which would mean a power factor of less than 50 per cent. This, therefore, indicates the impracticability of making a good synchronous motor which is able to drop out of step and operate as a good induction motor. The two conditions are conflicting, when running conditions are taken into account. A good synchronous motor therefore will not make a good induction motor, when carrying load.

Francis B. Crocker: I do not think there is time, when we have such an important and difficult paper to discuss, to defend the Standardization Rules, but there is opportunity, I believe, at the present time, to say that the Institute's Standards Committee is in existence, and that this committee is considering the revision of the rules, and any points of that kind which need consideration or revision should be presented to the committee.

I think also that the Standardization Rules should be revised from time to time. What may now be the actual wording of them may require modification as greater knowledge and change of practise takes place. In fact, I think it would be very extraordinary, and perhaps very undesirable, if they should remain unchanged, and not be revised from time to time. They have already been completely revised twice since their inception, and several other important changes and additions have been made when they were needed.

I think the point that Mr. Lamme has just spoken of is a thing we should bear in mind. Two machines, the synchronous motor and the induction motor, are shown to be more alike than we have previously considered, having been regarded, in fact, as quite different. After all, they are quite alike, and, of course, the same laws necessarily apply to both, but, unfortunately, it does not seem to be possible to make a compromise machine which would have the advantages of the induction motor in starting up, and the advantages of the synchronous motor in being able to have leading current and improve the power factor of the other apparatus. If such a result could be obtained, there would be a great field for a motor which would have the advantages of both.

C. P. Steinmetz: Mr. Fechheimer's very valuable paper is especially interesting to me, as I always had a very strong predilection for the synchronous motor, especially its larger sizes, since I consider this type of alternating-current motor as decidedly superior in its electrical characteristics, in its reaction on the electrical system, and more particularly with regard to power factor and voltage regulation. The synchronous motor does not spoil the power factor, but can operate at unity power factor, or can be used to improve the power factor spoiled by other apparatus.

The synchronous motor gives a fixed voltage point determined by its direct-current excitation, and thereby is able to, and does, hold up the voltage or pull down the voltage, depending on the conditions of the system, and thereby can be used to, and does, control the voltage of the system, especially in long-distance power transmission, where voltage regulation is more difficult. This is a very important characteristic, as the experience on the Pacific slope since the early days seems to have shown.

The synchronous motor has no starting torque, as such. It starts as an induction motor. It has not always been realized, especially with the squirrel-cage synchronous motor, that is, a synchronous motor provided with the amortisseur winding, how large a starting torque you can get from it, and it is not completely realized today. When we first considered the introduction of the squirrel-cage pole face winding in the synchronous motor, to give it powerful starting characteristics, we made a number of investigations which were rather startling. With a standard alternating-current generator of moderate size, provided with squirrel-cage windings, we determined the torque characteristics from standstill to synchronism, and found that the maximum torque of the machine as an induction machine was materially higher than the maximum torque of the same machine as a synchronous motor at unity power factor, with the same terminal voltage applied.

That means you can provide any desired starting torque in the synchronous motor. In giving the powerful starting torque to the synchronous motor by means of the squirrel-cage winding or amortisseur winding we naturally meet with the same difficulty we meet with in the induction motor, that the requirements at standstill and requirements at speed are opposed to each other. High torque at standstill requires fairly high secondary resistance. To bring high torque up close to synchronism requires very low squirrel-cage resistance. Now, in the synchronous motor, it is not merely sufficient to start from rest and run up to some speed, but we must run up so close to synchronism that the motor can pull into synchronism, into step; that is, we must go to a fairly low slip. The ability of the machine to pull into synchronism depends on the slip, and therefore the resistance, of the squirrel cage, and on the momentum of the moving masses, and also it depends very essentially on the mechanical configuration of the stator and rotor, as you can easily see by considering a machine with uniform reluctance all around, like a standard induction motor. Such a machine, without direct-current field excitation, could never pull into synchronism, and with the direct-current field excitation it is less able to pull into step than a machine with definite polar projection, and in the latter, also, we naturally find very wide differences, depending on the configuration of the polar structure of the machine.

In the early days of the synchronous motor, twenty years ago, when we built the first of these machines, we were very much afraid of the machines not being able to start off, and we provided three-phase bar windings in the field poles, brought out to a switch, to be able to insert resistances in starting, and afterwards to short-circuit them. Fortunately, experience showed that such complication was not necessary, and it was very soon abandoned. However, it would be extremely desirable if we could design the squirrel-cage windings of the synchronous motor, and probably also of the induction motor, so that their resistance would automatically vary to suit the conditions, from high resistance at standstill to very low resistance at speed.

Mr. Fechheimer mentioned the question of the short air gap. In the induction motor start of the synchronous motor, a short air gap is advantageous within certain limits, just as within other limits a short air gap is advantageous with the synchronous motor, but when you consider a still further decrease of the air gap, you reach a point where a further reduction of the air gap becomes objectionable in the starting of the synchronous machine as an induction motor, where we lose again by further reduction of the air gap. Decreasing the air gap, with the same size and relative position of stator and rotor slots, etc., at the same volt-ampere input, the average starting torque increases, but finally it increases very little. At the same time the irregularity of the starting torque increases, that is, the uniformity of the torque in different positions decreases.

What counts in the starting of the machine is not the average starting torque, but the minimum starting torque, the starting torque in the minimum torque position, and this depends on the relative proportions of air gap and width of slot, and also on the relative number of stator and rotor slots.

To get a reasonably uniform torque with a small air gap means very many narrow slots, which is uneconomical in general in the synchronous motor, and impracticable in a high-voltage machine, but with such a reasonable number of stator and rotor slots as is economical, and even as is permissible, in the synchronous motor, there is a limit in the air gap below which you cannot go without impairing the starting of the machine as an induction motor, by decreasing the torque in the minimum torque position.

We usually think of a large air gap as producing a high exciting current, and so it does in the induction motor, but the high exciting current counts in proportion to the total current. An induction machine would be inoperative if the magnetizing current were 200 per cent of full load current. In the induction motor starting of the synchronous motor such a magnetizing current of 200 per cent is unappreciable, if you consider the synchronous machine starting by auto-transformer at half terminal voltage, twice full load current, which means taking from the line only full load volt-amperes: 200 per cent magnetizing current, referred to half voltage and double current, is only 50 per cent, and would thereby increase the total current only very little.

If, instead of allowing a nominal 200 per cent exciting current, you would go down to as low an exciting current as is the limit in the poor induction motor, or 50 per cent, the increase of irregularity of the starting torque would be very much greater than the percentage decrease in the total of current, and therefore, to get a minimum starting torque equal to that which you get with the bigger air gap, you would have to increase greatly the volt-ampere consumption. Thus it would be an engineering mistake to reduce the air gap still further.

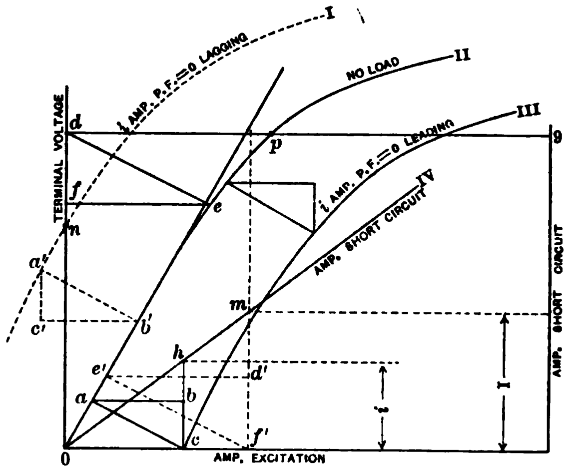
You see that the conditions in the starting of the synchronous motor are different, with regard to magnetizing current, from what they are in the running of the induction motor, and economical proportioning requires a larger air gap in the synchronous motor starting than in the induction motor operation, although there is naturally a limit in the size of the air gap, beyond which it is uneconomical to go.

The last point which I desire to make has reference to Standardization Rules. I would like to say here to you what I have said before: There is no use in kicking against the Standardization Rules or objecting to them. Instead of saying that such and such a rule is unsatisfactory and should be changed, say how it should be changed, and give the evidence proving your contention, formulate a better rule and you will find that Mr. Lamme and myself, who have the very questionable pleasure of providing for the changes, will be delighted to act upon your suggestion. But a mere statement that the rules are not satisfactory, means nothing, and we cannot act on such a statement until something better is offered.

We know that things had to be put in the rules, as representing the best that could be obtained with the limited experience and knowledge had of certain subjects. Now, what we want is to be provided with the data by which we can correct any existing rules that are not satisfactory, and we shall be delighted to do so, but, as I say, a mere objection to the rules means nothing. We know ourselves that many things should be changed, and the only question is how to change them and prove how the change should be made.

Bradley T. McCormick (by letter): During the period of starting, the self-starting synchronous motor acts as an induction motor of special type, but when synchronous speed is attained, the machine operates as a synchronous motor under the special condition of no excitation, until the field circuit is closed.

While the starting characteristics of the self-starting synchronous motor, before it has reached synchronous speed, can only be determined by methods which are more or less empirical, the current input to the motor after it has reached synchronous speed, but before the fields are excited, can be accurately determined. Although this current is less than the starting current at rest, it is still of some interest, as it represents one of the points on the current-speed curve which can be determined easily and with accuracy.



In the figure presented herewith, curve II shows the no-load saturation curve of a synchronous motor, while curve III shows the saturation curve at a leading power factor of zero, with the full load current of i amperes per phase. Curve III is the path traced by the point c, as the triangle abc moves upwards in such a manner that point a follows curve II. The line ab is the armature reaction expressed in terms of amperes excitation, and bc is the reactance drop of the stator in volts.

Curve I is the full load saturation curve for zero power factor lagging, and is obtained by turning the triangle *abc* into the position *a′b′c′*, and moving along curve II as before.

The point *n*, where curve I crosses the axis of ordinates, locates the terminal voltage at which the motor will draw full load current when running at synchronous speed without excitation. In order to find the current drawn on full voltage *od*, draw *de* parallel to *ac* and construct the triangle *efd* similar to *abc*. The required current can either be found from the relation

$$I = i \frac{f\,e}{a\,b}$$

or by transposing the triangle into the position *e′f′d′* and taking the current from the short-circuit curve at the point *m* directly above. Were it not for the saturation of the iron, which causes the no-load saturation curve to deviate from a straight line, the perpendicular line through *f′d′* would cut the no-load saturation curve at the point *p*.

The above treatment can therefore be simplified into the following simple rule:

Neglecting the saturation of the magnetic circuit, a synchronous motor running on any voltage at synchronous speed without excitation, will take from the line a current equal to the short-circuit when run as a generator with the fields excited to a value corresponding to the above-mentioned open-circuit voltage.

The copper loss of a squirrel-cage winding of a self-starting synchronous motor can be calculated by the same method as that employed for induction motors. The following formula I have used with good success for induction motors, and although it does not go into the refinements to the extent of Mr. Fechheimer's formula, it gives results whose accuracy falls within the variation of the resistance of the composition metal in the end rings.

Squirrel-cage copper loss in watts

$$= \left[\left(\frac{s}{\pi}\right)^2 2\,R_r + R_b\,s\,p\right] I_b^2$$

I_b = the current per rotor bar.
R_b = the resistance of one rotor bar.
s = the number of rotor bars per pole.
p = the number of poles.
R_r = the resistance of one end ring measured clear around its circumference.

C. J. Fechheimer: It is indeed gratifying to me to have heard from so many prominent engineers that most of the conclusions at which I arrived in my paper are in accordance with their own views. I was to some extent expecting opposition to a number of my conclusions, especially in reference to the size of air gap and the good results which it is possible to obtain with the synchronous motor at starting as compared with the squirrel-cage induction motor.

Mr. Williamson speaks of the prevention of the current rush accompanying the throwing over to full voltage when the fields are excited with direct current. The method which I favor consists in keeping the stator circuit closed and at the same time having sufficient current in the fields of the motor to enable the power factor to come approximately to unity when throwing on the higher voltage. In this way the current is reduced rather than increased.

The explanation offered by Messrs. Williamson and Lamme of the tendency to refuse to accelerate beyond half speed when the field circuit is closed upon itself, I believe accounts for the phenomenon better than the theory I advanced. After more mature consideration, I am quite willing to agree with these gentlemen that this tendency is due not to higher harmonics, but rather to the single-phase reaction of the rotor upon the polyphase stator.

In regard to Mr. Newbury's question in reference to the rotor construction of the motors which were tested, I would inform him that the solid pole rotors were not provided with any kind of squirrel-cage winding; only those curves shown in Figs. 7 and 8 pertain to motors with amortisseur windings, the construction consisting of bars in the poles which were connected at the ends with continuous rings. Figs. 7, 8 and 9 refer to the same motor; the amortisseur windings had been removed in tests plotted in Fig. 9.

In general, I do not think it advisable to connect the field rheostat in series with the rotor at starting. It is possible that the motor Mr. Newbury has in mind is different from those I am familiar with. It is seldom that the field rheostat has a resistance more than four times that of the field. In order to obtain more favorable starting conditions the resistance in the field circuit should be approximately equal to the reactance thereof. Usually the reactance is more than one hundred times the resistance. Hence, with the rheostat in series, the resistance in the field circuit would be approximately equivalent to one-twentieth of the reactance. Therefore, this resistance is entirely too small to secure small line current for a given torque. The unfavorable results obtained by short-circuiting the fields or by having a comparatively small resistance in series with them, is, as one would suppose, less marked when the amortisseur winding is present than when it is removed. This can be seen by a study of Figs. 3, 4, 7, 8 and 9.

It would seem that Mr. Newbury has achieved remarkably good results in the 200-kv-a. synchronous motors, and this would tend to bear out more fully the statements that have been made by others contributing to this discussion, that the synchronous motor, when properly and carefully proportioned for starting conditions, can be made comparable to the squirrel-cage induction motor.

In regard to Mr. Dudley's statement to the effect that all of the losses in the rotor are not necessarily productive of torque at the instant of breaking loose from rest, I would refer him to item 7 in the paper under " Determination of Starting Characteristics with Laminated Poles and Amortisseur Winding " as follows: " Losses due to a pulsating component of flux not productive of torque." This I believe covers the condition which Mr. Dudley pointed out. In this connection, however, I would call attention to the inaccuracy of commercial starting tests. When an error from tests is as great as Mr. Dudley describes, it is usually due to the pronounced effect of bearing friction, to overcome which a considerable portion of the developed torque is required.

There is no doubt that the high potential induced in the rotor circuit is undesirable. From comparisons which I have made between solid and laminated pole machines, I am inclined to believe that solid pole machines give rise to lower induced potential than those with laminated poles. As Mr. Foster says, however, much depends upon the resistance of the amortisseur winding. For a given flux entering the pole heads the induced potential in the rotor coils is decreased as the resistance of the amortisseur winding is lowered. There is, however, this disadvantage—the line current drawn for a given starting torque is materially increased, and the starting torque for a given impressed electromotive force on the stator terminals reduced, by the low-resistance squirrel-cage winding. On the other hand, if a carefully proportioned high-resistance amortisseur winding is used, less flux and less stator potential is required for a given starting torque, and with this lower flux I do not believe a prohibitively large potential is induced in the rotor coils. Comparisons I have made lead me to believe that the induced potential for *a given starting torque* with a high-resistance squirrel-cage winding is not very different from that with a low-resistance winding. On the other hand, however, with solid poles, the induced potential in the rotor coils is much lower than with a high-resistance or even low-resistance squirrel-cage winding when the poles are laminated, due, of course, to the skin effect; at the same time the currents are crowded into such a thin shell that the torque is increased rather than decreased.

As Mr. Foster reminds me, the statement which I made in my paper in respect to the number of slots in the rotor as being dependent upon the judgment of the designer, is somewhat vague. If the motor is to be directly coupled to an unloaded, reciprocating air compressor, the starting torque should be greater than the torque during acceleration. In such cases, therefore, a high-resistance winding is desirable. The variation of starting

The formula which Mr. McCormick has given for calculating losses in the conducting circuit of squirrel-cage induction motors is similar to that which I have used. It depends upon a sinusoidal space distribution of flux. I do not think that we could apply this formula to the case of a synchronous motor in which the distribution of flux is so far from being sinusoidal due to the peculiar rotor configuration.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 25, 1912.

DIRECT-CURRENT AND ALTERNATING-CURRENT MILL MOTORS FOR AUXILIARY DRIVES

BY BRENT WILEY

DIRECT-CURRENT MILL TYPE MOTOR

Motor drive for the auxiliary apparatus of steel mills, including tables, screw-downs, cranes, charging machines, etc., has been used for about twenty years. The application of motors to the various machines was naturally a very gradual process. The conditions were very unusual, as the work was of an extremely severe nature, requiring frequent starting and stopping, rapid acceleration and sudden stops. Motors had to operate in very hot and dirty places and in a majority of cases gear drive was used. The mills were operated for 24 hours a day, six days a week. The manually operated direct rheostatic controller was the only type available, and this meant heavy overloads during starting and reversing periods.

These several applications require motors ranging from about 5 h.p. to 150 h.p. on an intermittent rating basis, with speeds ranging from about 800 to 450 rev. per. min. respectively.

Motors for industrial purposes were available only in a few types and these were not very suitable for the severe requirements. The best solution of the problem was to modify the types of series-wound motors used for street railway work, for the sizes above 25 h.p., and the lighter types of motors were used for the smaller sizes. Changes were made in the frames of the railway motors, adding feet and suitable supporting lugs, omitting countershaft brackets for some styles, making windings suitable for 250-volt instead of 550-volt circuits and modifying the full load speeds. There are several hundred thousand horsepower of these motors which have given years of good service in the iron and steel industries, but a careful study of the results showed that the cost of maintenance was high, and for the more severe reversing service the reliability was often questionable. A comparison of the service given by the older types of motors and by the more recent mill type motor will be given later.

About 1905 a very careful review of steel mill requirements was made, in consultation with a majority of the electrical engineers of this industry, to ascertain the features which should be included in a mill type direct-current motor. Many of the electrical engineers of the steel companies keep very accurate records of the service given by the motors installed. The repairs on each motor are kept in detail, in some cases, although the armature repairs are usually the only items compiled by yearly records. These data were of particular value in determining the principal features of improvements to be incorporated in the new motor. Thus, by combining the skill and experience of the manufacturer and the mill engineer, a most satisfactory design of motor has been developed.

The principal features that have been recommended to be included in the design of a motor for mill and similar work are as follows:

1. Motor designed for intermittent service, 220 volts, with series and also compound windings, the latter to give approximately twice full load speed at no load.
2. Sizes ranging from 5 h.p. to 150 h.p. intermittent rating, with moderate speeds.
3. Large massive *steel* frame with well ribbed foot supports.
4. Large shaft.
5. Liberal face and pitch of pinion and gears.
6. Bearings split, bolted together and provided with eye-bolts to facilitate handling of armature.
7. Oil ring lubrication and dust-proof bearings.
8. Improved methods of preventing oil creepage along armature shaft to winding and commutator.
9. Tapered shaft extension, with retaining nut exterior to pinion, to facilitate removal of pinion or brake wheel.
10. Armature built on a spider to facilitate removal of shaft and insure rigid construction.
11. Fire-proof windings (armature and field coils.)
12. More substantial methods of holding armature coils in place, including banding wires sunk below surface of laminations and coil supports at end.
13. More liberal commutator surface.
14. More substantial and better insulated type of brush holders.

15. More convenient design of frame for inspection and replacement of brushes or brush holders.

16. Commutating pole features which give the following advantages:

   a. Practically perfect commutation under all conditions of load and voltage within the capacity of the motor.

   b. No injurious sparking when the motor starts with very high torque or is momentarily overloaded.

   c. Greatly increased working capacity, owing to the increased commutating ability.

   d. Low repair expense and great reliability of operation, owing to long life of commutator, brushes and brush holders.

As many parts as possible should be made in duplicate, including armature shaft extensions on each end, bearings, field coils and brush holders. These features simplify the construction and also the maintenance of the motor. These several points can best be amplified by referring to the engineering consideration of the details of design.

The frame should be of cast steel and arranged for ease of inspection of parts, with large openings for the inspection of the commutator and adjustment of the brushes.

The armature should be so designed that the shaft can be removed without disturbing the windings or the commutator. The flywheel effect of the armature should be low, to minimize power required for acceleration and reversing.

The insulation of the armature and field coils should be capable of standing high temperature (at least 150 deg. cent.) without undue deterioration, and particular care should be exercised in safeguarding the windings against mechanical injury that might be occasioned by excessive speed of armature and vibration of motor, due to sudden shocks of stopping and reversing.

The commutator should be of liberal design and the current density of the brushes should be approximately one-half that used for the older types of motors, being about 40 amperes per sq. in. (6.45 sq. cm.) for the average motor. Grounding of the commutator at the V-rings has been one of the serious troubles in the older types of motors and particular care should be taken to guard against this collection of grease, oil and dust. It would be well to enclose the commutator thoroughly in the rear, and where oil ring lubrication of the bearing is used, the following suggestions are made to prevent creepage of oil along the shaft to the commutator and windings: oil bearings drilled at the ends to provide drainage back into oil cells; halves of bearing bolted together; splash guard provided around oil ring and oil thrower used on shaft.

It would be an advantage to have split bearings to facilitate their replacement without disturbing pinion or brake wheel; and a projecting lug to prevent turning of the bearing, instead of a dowel pin, would be an improvement. For handling the armature, a permanent eye-bolt in the bearing provides a ready means and is much preferable to the use of a rope sling.

Long life of the bearings is a very desirable characteristic and this is best secured by means of oil ring lubrication. It would be well, however, to have the bearing so designed that grease lubrication can be easily provided for some cases, such as a motor that has to be tilted through a wide angle.

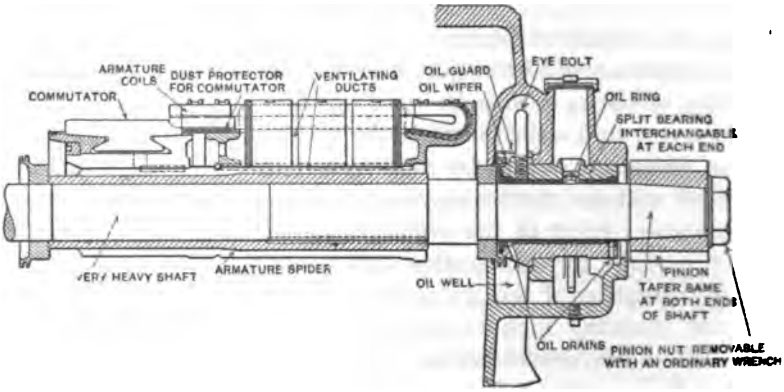


FIG. 4—SECTIONAL VIEW OF ARMATURE AND BEARING HOUSING

The brush holder should be of rigid design, firmly held in place and well insulated to prevent grounding, as motors are required to operate in places that are dirty, sometimes very hot and often quite damp.

A great deal of attention has been given to the subject of rating for mill motors. The service for which they are used is of an intermittent nature with wide variations of load within short time intervals. As a general basis, the ratings are given as the horse power developed with a maximum temperature rise of 75 deg. cent. in the core and windings and 80 deg. cent. on the commutator, for continuous operation at normal voltage for a period of one hour. It would be well, however, to give a table of ratings ranging, say, from 5 hours to ½ hour, and as

FIG. 1—DIRECT-CURRENT MILL TYPE MOTOR [WILEY

FIG. 2—REMOVING ARMATURE AND BEARINGS [WILEY]

FIG. 3—UPPER HALF OF FRAME WILEY]


[WILEY]

FIG. 5—BRUSH HOLDER


[WILEY]

FIG. 6—ARMATURE BEARING


[WILEY]

FIG. 10—LIFTING ROTOR AND STATOR FROM FRAME, A-C. MILL TYPE MOTOR


FIG. 11—ROTOR [WILEY]


FIG. 12—STATOR [WILEY]

the motor is in actual service only a portion of the time, the ratings should be given at reduced voltage at the motor terminals. The voltage at the motor terminals is practically proportional to the speed during the accelerating and retarding periods, and a very practical way to estimate the average voltage is to plot the speed-time curve of the motor for the particular cycle in question.

To select a motor for intermittent duty, having given the load, the time on and the time off, a very practical method is to estimate the continuous capacity required, by the square root of mean square method.

In the majority of cases, intermittent service means the repetition of a rather definite cycle of operation for several hours. This cycle should be plotted in order to determine the load, the time on and the time off. Take, for example, the hoist of an ore bridge with the following conditions:

Closing bucket	50 h.p.	8 seconds.
Hoisting bucket with load	120 h.p.	10 "
Trolley in	0 h.p.	10 "
Opening bucket	20 h.p.	8 "
Trolley out	0 h.p.	10 "
Lowering bucket with dynamic braking	50 h.p.	9 "
Total cycle		55 seconds.

This cycle to be repeated for a total period of 5 hours.

The two principal factors which are taken into consideration in determining the proper size of motor are commutation and capacity from the standpoint of heating. Making proper allowance for the peak load due to acceleration, the data given above are sufficient to determine the question of commutation, but the heating effect of this varying load is a rather complex problem. It is probably best expressed in terms of an equivalent continuous load, it being noted that the voltage at the motor terminals is reduced in accordance with the speed-time curve, as mentioned above.

A practical way of approximating this equivalent continuous load is by means of the square root of mean square method, which is as follows:

Square the load and multiply by the time for each part of the cycle; add the several results; divide by the total time of one cycle, and extract the square root of the quotient. The result is the load which, if applied to the motor at the average voltage, will produce the same heating effect as the varying load. Thus, for the example given above,

$$\begin{array}{r}
50^2 \times 8 = 20{,}000 \\
120^2 \times 10 = 144{,}000 \\
20^2 \times 8 = 3{,}200 \\
50^2 \times 9 = 22{,}500 \\
\hline
55\overline{)189{,}700} \\
3{,}450 \quad \sqrt{3{,}450} = 59 \text{ h.p.}
\end{array}$$

It would therefore be a convenient reference to have the motor ratings given for various periods ranging from 15 minutes to 5 hours on the continuous basis, and at reduced voltage at motor terminals, to provide a ready reference, as for example:

5	hr.	62	h.p.	650	rev.	per	min.	series-wound.
4½	"	63.5	"	640	"	"	"	"
4	"	65.5	"	630	"	"	"	"
3½	"	68.5	"	618	"	"	"	"
3	"	71.5	"	605	"	"	"	"
2½	"	76.5	"	577	"	"	"	"
2	"	83	"	550	"	"	"	"
1½	"	91	"	515	"	"	"	"
1	"	100	"	475	"	"	"	"
½	"	150	"	400	"	"	"	"
¼	"	190	"	360	"	"	"	"

Experience shows that in general steel mill work the all-day operation of motors on intermittent service gives a heating effect equal to a continued repetition of the cycle of operation for five hours. This is because of unavoidable delays encountered in actual service. It is therefore usually safe to select the size of motor for all-day service on the five-hour basis.

Regarding the performance, the mill motor should be capable of standing a heavy overload current, 300 or 400 per cent of full load current, for short intervals, say 5 seconds, without injurious sparking, and the momentary safe torque should be at least 100 per cent more than this value. These features increase the working capacity of a motor for some severe applications, as the heating becomes the limiting factor instead of the commutation, and as fire-proof insulation is provided, a safe working temperature is assured, much higher than that of the older types of motors. Cotton insulation will stand a temperature of 90 deg. cent. without undue deterioration and

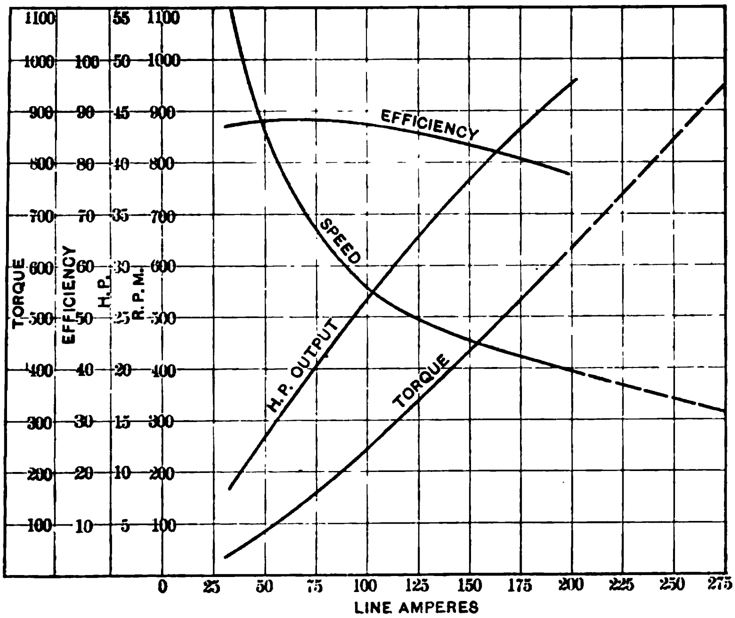


FIG. 7—CHARACTERISTIC CURVES OF 30-H.P. SERIES-WOUND MILL MOTOR

(1 hr.-75 deg. cent. temperature rise. 230 volts)

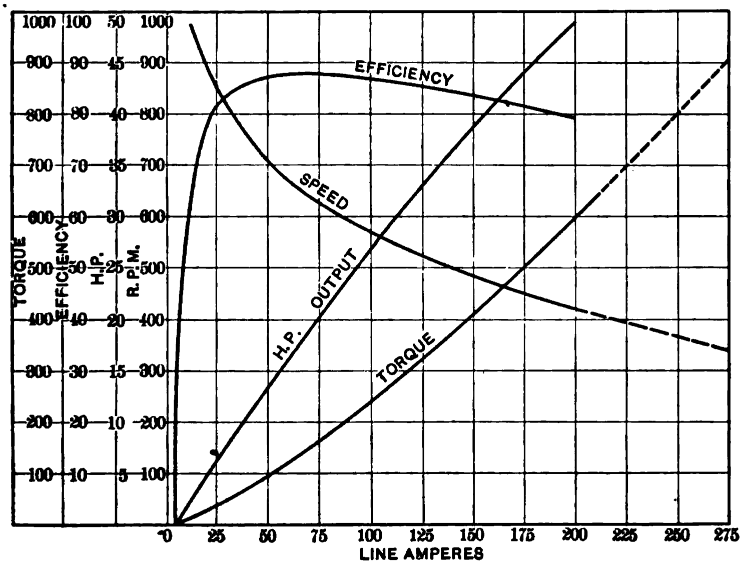


FIG. 8—CHARACTERISTIC CURVES OF 30-H.P. COMPOUND-WOUND MILL MOTOR

(1 hr.-75 deg. cent. temperature rise. 230 volts)

the insulation of mill motor windings should stand 150 deg. cent. safely, which is more than a 60 per cent increase.

The advance in the art of electrical engineering in the steel industry insures a more accurate selection of motor size for the various applications; and the recently developed types of controllers provide special protection against unnecessarily severe conditions being imposed on the motors. While these factors are a distinct advantage, it is the many points of superiority in design which insure the durability and reliability of the mill type motor. Data have been obtained from the records of the electrical departments of several of the large steel companies, relative to the service given by railway crane type, 220-volt, direct-current series motors and mill type motors.

ONE-YEAR RECORD OF ARMATURE REPAIRS

	25-h.p. railway crane type.	25-h.p. mill type.	50-h.p. railway crane type.	50-h.p. mill type.
On crane	742	117	341	17
On floor machinery	247	68	80	30
Total	989	185	421	47
New armature coils (sets)	400	6	306	4
New commutators	255	0	181	0
New shafts	71	0	30	0

Average plant operation during year, 75 per cent of normal capacity.

It should be noted that the railway crane motors have been in service for more than 10 years and the mill motors less than two years, average, and therefore the figures given above are not on an even comparative basis. Making a liberal allowance, however, for deterioration and wear for the mill type motors, as figured from the records of those in service for the longest period, the comparison of the durability of the two types of motors is as follows:

	Average life of armature.
Railway crane type motors	2½ years
Mill type motor	10 "

ALTERNATING-CURRENT MILL TYPE MOTOR

The majority of power station improvements of industrial plants have of recent years included alternating-current generators, principally on account of the economy of transmission and wide range of practical sizes of generator units as compared with direct-current power. The steel industries have followed this practise with but few exceptions, and, principally on account of slow motor speeds sometimes required, 25 cycles has practically been adopted as a standard. It is both economical and desirable to utilize this power as directly as possible, and alternating-current motors are preferable for the auxiliary drives, except possibly for a small percentage of applications where the work is very severe, requiring very rapid acceleration and frequent reversals. The direct-current series-wound motor has characteristics best suited for these particular requirements, but on analysing steel requirements in general, it will be found that these are few.

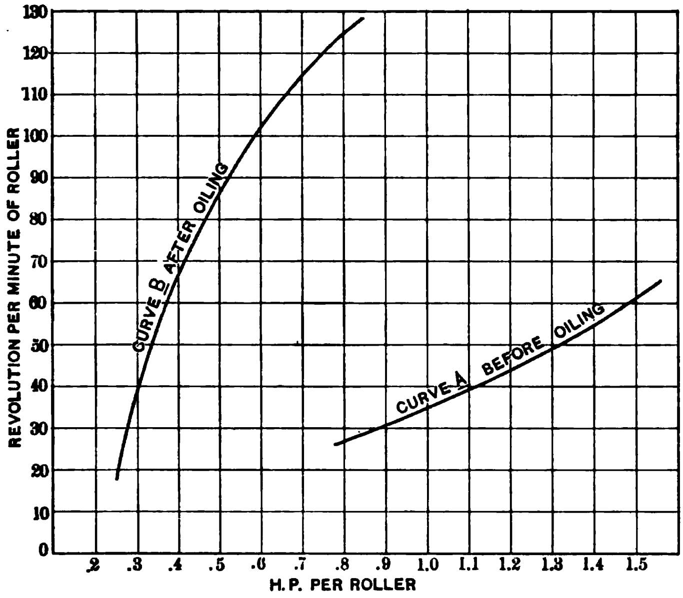


FIG. 9—MOTOR-DRIVEN ROLLER TABLE
22 rollers, 1300 lb. each

The general features of the alternating-current mill motor to meet these severe conditions should be the same as recommended for the direct-current motor, with sizes ranging from about 5 h.p. to 150 h.p. and speeds ranging from 750 to 375 rev. per min. (synchronous).

The frames should be of cast steel and the construction of motor very strong and rigid throughout. The design should be such that all parts are easily accessible for inspection, adjustment and repairs. Reliability and durability should be given particular attention, and it is recommended that fire-proof windings of rigid construction, firmly held in place, large shafts and other features to insure liberal safety factors throughout be included.

The performance should be such that high starting torque is obtained with comparatively low starting current, and the pull-out torque should average about three times full load torque.

In order to obtain the best starting conditions with the alternating-current mill motor, a careful study of the requirements and the motor characteristics is necessary and is a much more important feature than for the direct-current motor. This point can be emphasized best, perhaps, by giving a review of the starting characteristic curves of the alternating-current motor.

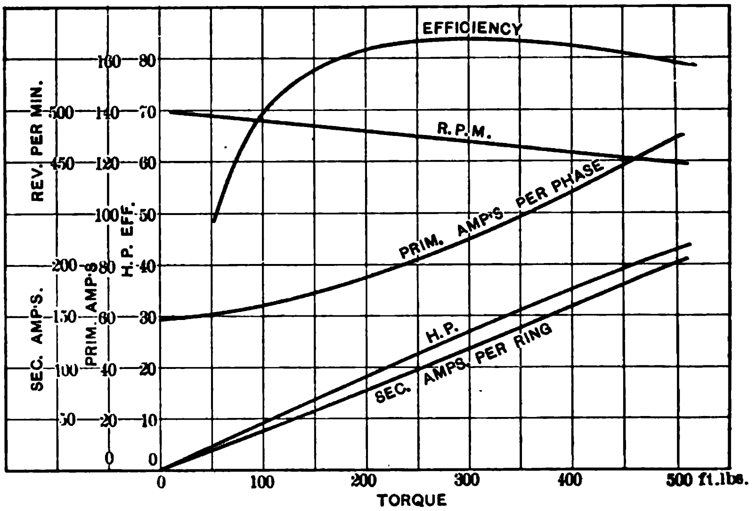


FIG. 13—CHARACTERISTIC CURVES OF 33-H.P. WOUND ROTOR A-C. MILL MOTOR

(1 hr.-75 deg. cent. temperature rise)

*"In determining the best starting condition, the current supplied to the primary must be considered in connection with the speed-torque curves. This current is plotted with the

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*Extract from an address on "The Polyphase Motor" by B. G. Lamme, presented at the twentieth convention of the N.E.L.A., 1897.

series of speed-torque curves shown in Fig. 14. Referring to this figure, curve *A* represents the primary amperes in terms of torque. Starting at the point *B* of no load or zero torque, it rises at a nearly uniform rate until maximum torque is approached, that is, below the point of maximum torque the current is nearly proportional to the torque, but beyond this point, the current continues to increase, and reaches a maximum at the torque represented by zero speed. At reversed speed, this current is further increased. This one current curve holds true for all the speed-torque curves *a*, *b*, *c*, *d*, etc.

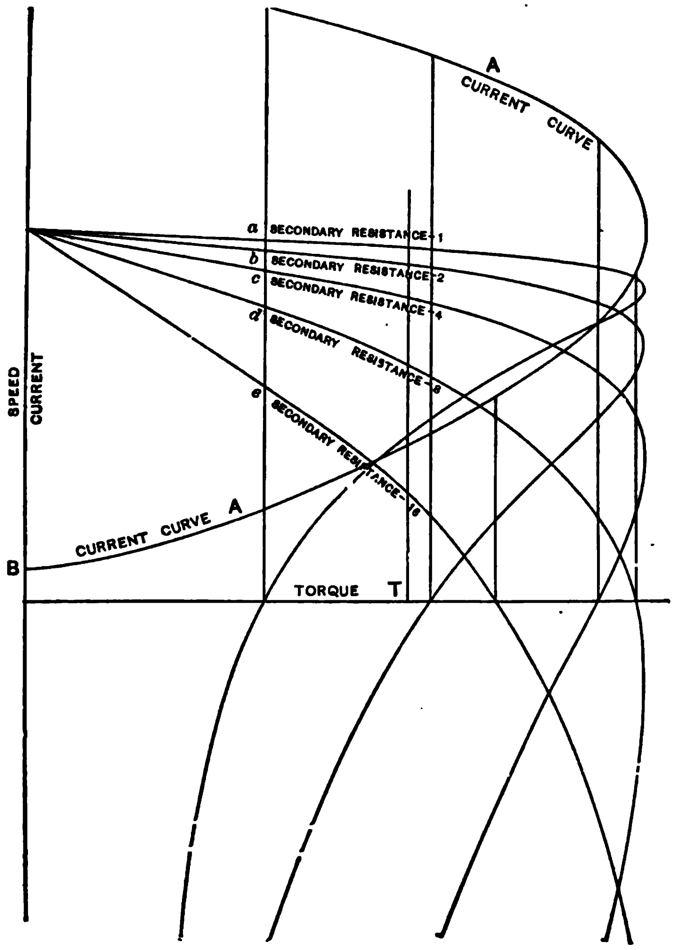


FIG. 14—FULL SPEED TORQUE AND CURRENT CURVES OF POLYPHASE MOTOR WITH DIFFERENT SECONDARY RESISTANCES

"Comparing the different curves, we see that *a* takes the most current at start, and gives low torque, *b* takes less current than *a*, and gives more torque; *c* takes less current than *b*; *d* takes less current than *c* and gives the maximum torque at start; *e* takes less current than *d*, and develops less torque, but the current and torque are very nearly in proportion over the whole range. From this we see that a speed-torque curve of the form *d* or *e* is decidedly better for starting than *a* or *b*. But for running at less than the maximum torque, there is no advantage, so far as current is concerned, in curve *d* over curve *a*, and the speed regulation of *d* is poor.

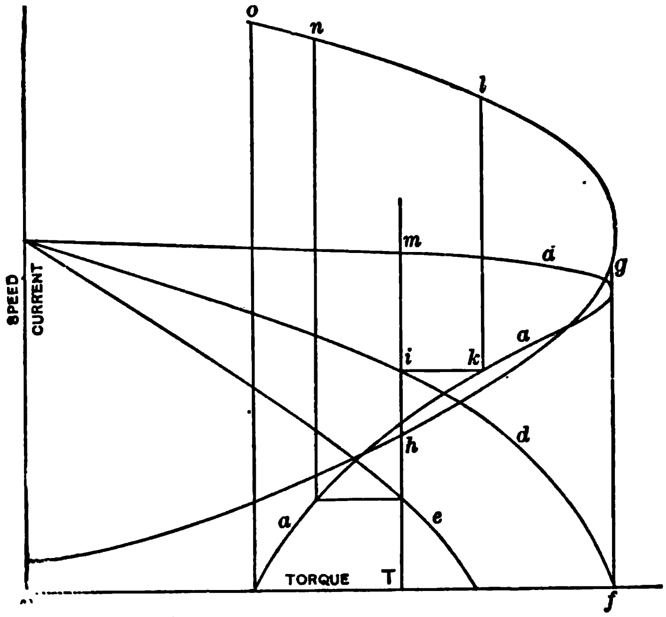


Fig. 15—Starting Conditions with Variable Secondary Resistance

"Fig. 15 represents the condition of speed, current, etc., when a variable secondary resistance is used in starting. The motor starts with torque indicated by *f* on the curve *d* and takes current *g*. The current falls to *h* while the speed rises to *i* which corresponds to the normal torque *T* at which the motor will run under the given conditions as long as it operates on curve *d*, the speed meanwhile remaining at *i*. If the resistance in the secondary is now short-circuited, and the load thus shifted to the speed-torque curve *a*, the torque at the speed *i* increases to *k* on the torque curve *a*. The current corresponding to this is *l*; as the torque *k* is greater than the normal torque *T*, the motor will increase until normal torque is reached again at *m*, while the current falls from *l* to *h*.

"At the moment of cutting out the secondary resistance, there was a very considerable increase in the current. By arranging the starting resistance in the secondary so that the motor will start at some curve intermediate between *a* and *d* and thus take more current at start, somewhat less would be required upon switching to curve *a*. If curve *a* is used for starting, and if the torque required when speeding up is greater than at the point where curves *a* and *e* cross each other, the motor will not pull up, because in switching from *e* to *a* the torque falls, and the motor will stop. The current in switching over increases to *n* and then rises to *o* as the motor stops. In this case, the resistance that gives curve *e* is too great, and a lower starting resistance is required.

"By making several steps in the secondary resistance, so that it can be cut out gradually, the motor can be made to pass through a series of speed-torque curves with much smaller variations of current than shown in the preceding diagram."

It can be stated generally that in the case of the alternating-current motor, the torque is proportional to the current, with properly regulated resistance steps. In starting, the torque of the direct-current series motor is in a somewhat greater proportion—twice full-load current giving 2½ times full-load torque (see Fig. 7)—and it is not necessary to govern the cutting out of the resistance so accurately to insure a continued high torque. These conditions can, however, be properly provided for in the case of the alternating-current motor. Magnetic controllers can be provided which automatically govern the cutting out of the resistance to the best advantage, and with the hand-operated controllers, a little training and care on the part of the operator will give the desired results. These inherent features of the alternating-current motors protect the driven machines from abnormal shocks, as well as protecting the motors themselves from mechanical abuse.

The direct-current series-wound motor has high speed at light loads, which is a desirable feature for the hoist of a crane motor. As the speed of the alternating-current motor varies but little with change of load a somewhat larger motor is required to give a speed which will be equivalent to the average of the light-load and full-load speed as given by the proper direct-current motor. For example, if the hook speed is 40 ft. (12 m.) per minute no-load and 20 ft. (6 m.) per minute full-load with the direct-current motor, an alternating-current motor capable of giving a speed of 30 ft. (9 m.) per minute is required to accomplish a cycle of operation in the same time. In the case of the bridge travel and the trolley travel of the crane, the difference in motor characteristics is not so apparent, as the load is practically constant when up to speed.

Motors designed with liberal starting torque will give satisfactory acceleration.

The proper application of the alternating-current mill motor to give satisfactory service is not only a question of motor characteristics, but more particularly includes a thorough understanding of the conditions to be met, and it is recommended that particular attention be given to the detailed analysis of requirements. With these more definitely established, a more general use of the alternating-current mill motor, with its many attendant advantages, is assured.

DISCUSSION ON "DIRECT-CURRENT AND ALTERNATING-CURRENT MILL MOTORS FOR AUXILIARY DRIVES" (WILEY). PITTSBURGH, PA., APRIL 25, 1912.

Alexander C. Lanier: Mr. Wiley's paper has brought out the principal demands made upon motors in mill and crane service and my remarks will be limited to direct-current motors suitable for such applications. Commutation is always a factor of first importance in the direct-current motor; service conditions met in mill work are much more severe than in the ordinary industrial application. During the operating cycle the load usually varies between wide limits, and momentary peaks may reach three or four times the one-hour rated load.

The commutating pole motor is particularly suitable for such conditions. I shall only mention in passing the long-recognized principle underlying commutating pole design. By providing at the point of commutation a flux closely proportional over a wide load range to the current commutated, its value in general such as to give straight-line reversal of current under the brush and its magnetizing current in series and therefore in time phase with the armature current, the commutating range of the machine is greatly extended. For motors in reversing service, with neutral setting of brushes, commutation is better provided for, in a properly designed commutating pole machine, under heavy overload conditions than in the normal non-commutating pole type at rated load. In the design of commutating pole motors of strongly drooping characteristics, slight over-compensation at normal load will add somewhat to the overload range of the motor. The short-circuit voltage per brush and per coil should also be kept within proper limits.

In commenting upon the root-mean-square method for selecting motors for a given service, with known operating cycle, and length of time during which the cycle is repeated continuously, attention is directed particularly to the utility of a table of ratings covering a wide range of time period as indicated in Mr. Wiley's paper. Besides the application in which there is practically continuous repetition of the cycle over five-hour periods, frequent cases arise in which the motor is subjected to very heavy loads of short duration, followed by long periods of light load or absolute rest. Since the temperature rise of a motor under loads of short duration is a function of the heat capacity of the machine more largely than its radiating properties, the short-time rating of the motor in such cases forms a ready basis for its selection.

M. A. Whiting: There is one point concerning which I should like to have Mr. Wiley go into a little further detail, *i. e.*, he states that the heating effect of a varying load is best expressed in terms of an equivalent continuous load with the voltage at the motor terminals reduced. I should be interested to know how great a reduction in voltage Mr. Wiley has in mind and just what conditions such a rating at reduced voltage is intended to cover. For example, it could be made to cover merely the operation of the motor during accelerating periods, during which the voltage impressed on the motor armature varies from zero to full line voltage, or it could take account of the probability of prevailing condition of low average plant voltage. Further information on this point would therefore be of interest.

The root-mean-square method, which Mr. Wiley explains and illustrates, is of course by far the best known and most widely used method for estimating the heating of a motor on a varying load, but in some cases this method introduces serious discrepancies. It is therefore of interest to consider under what conditions the discrepancies occur and in which direction they affect the result. This is not a criticism of the use of the root-mean-square method in general, but merely a consideration of its application with reference to certain cases. The accuracy of this method depends on the shape of the efficiency curve of the motor over the range of loads considered. Take for example, the curve in Fig. 7, covering a series motor with a nominal rating of 30 h.p. As the heating curve is not given, we may assume for the purpose of discussion that the continuous capacity of the motor is one-half the full load current. In using the r.m.s. method for a continuous cycle (*i.e.* for a cycle repeated continuously for, say, twenty-four hours) after determining the r.m.s. equivalent of the load we compare it with the continuous capacity of the motor for the allowable temperature rise. In doing this the assumption is made that the total *kw. losses* of the motor vary as the square of the load, or, expressed in other terms, the assumption is made that the *per cent losses* vary directly as the load. The efficiency curve assumed by the r.m.s. method therefore begins at the point of 100 per cent efficiency—zero load, and consists of a straight line extending down at an angle and intersecting the actual efficiency curve at the point corresponding to the continuous capacity of the motor (in the present case, Fig. 7 of Mr. Wiley's paper, assumed at half load as stated above). Where the actual efficiency curve follows very closely this straight line, the r.m.s. method will be very close. But in the figure under consideration the actual efficiency curve crosses this straight-line efficiency curve at a considerable angle, so that the actual losses at heavy loads are less, and at very light loads are greater than indicated by this hypothetical straight-line efficiency curve laid out in accordance with the r.m.s. assumption.

I have had occasion to work out a number of cases along this line (not, however, in connection with this paper), which show the following:

First, if the loads in a cycle are at all times below the basic value with which the comparison is made (*i.e.*, are at all times below the continuous capacity of the motor) the heating will be greater than indicated by the r.m.s. method (although, of course, still below the capacity of the motor).

Second, if the loads are all above this basic value, interspersed with periods of rest and periods during which the motor coasts without load, the heating will be less than indicated by the r.m.s. method.

Third, if the loads are partly above and partly below the basic value, the losses may be greater or less than indicated by the r.m.s. method. Where the loads vary above and below the basic value in this manner, the errors due to the r.m.s. method showing too low losses at light loads and too high losses at heavy loads, tend to compensate, so that on this kind of cycle the discrepancy will usually be much smaller than in cases 1 and 2.

Referring to the induction motor curve, Fig. 7, we note that the efficiency curve is more nearly level at overloads than is the case for the direct-current motors, Figs. 7 and 8, *i.e.* the losses for this induction motor deviate more greatly from the r.m.s. assumption, and the method is more inaccurate. In general, a motor with high iron losses and low armature and series field copper losses will vary more from the r.m.s. assumption than will a motor with large armature and series field losses and small iron losses.

To compare the relative accuracy of the r.m.s. method for open and enclosed motors we may refer to Fig. 7, and consider this efficiency curve as applying to an open motor having a continuous rating of 30 h.p. In this case the basic value assumed in using the r.m.s. method will be, as before, the continuous capacity of the motor (in this case 30 h.p.). If we draw a straight line efficiency curve on this figure, in the same manner as previously, but intersecting the actual efficiency curve at 30 h.p., these two curves lie close together over a considerable distance, and the r.m.s. method will therefore be much closer than in the case of the enclosed motor discussed above.

In practically every open motor of normal design the losses at the continuous rating of the motor are principally load copper losses, whereas with any enclosed motor, on account of the reduction in continuous output, the iron losses form a large percentage of the total losses at the continuous rating of the motor. It will in almost all cases be true, therefore, that the root-mean-square method is liable to greater inaccuracies when applied to an enclosed motor than when applied to an open motor.

R. B. Treat: There is a class of service to which the commutating-pole mill motor is not well adapted. We had an illustration on the screen of a screw-down motor and a front and back catcher table motor. This is the type of service referred to, requiring momentary high torque for very short times. The normal commutating-pole mill motor will easily stand 50 per cent over its rated load. At 100 per cent overload that motor will commence to spark. At 200 per cent overload the sparking of the brushes is worse than if there were no commutating poles present. Screw-down and catcher table service requires commutating capacity rather than heat capacity in the motor. The commutating poles should therefore be designed for the 200 or 300 per cent overload current, but such a design is not found in commutating-pole mill motors of a size necessary for screw-down or catcher tables.

It may be true that small commutating-pole mill motors (25 h.p., more or less) have been run satisfactorily in the factory with three, four or five times rated load. The design which permits this in a 25-h.p. size does not prevail in a 75- or 100-h.p. size. There is no comparison between a small motor on factory test and a large motor on screw-down or table service.

There is another feature, too. The peak current is instantaneous, mounts to its maximum value, and then drops off within a small fraction of a second. The flux set up by the windings on the commutating pole comes along a little later—after the current has subsided. It is not in synchronism with the load current. The load current is present without any commutating flux; there is sparking. The load current subsides, the commutating flux comes, and again there is sparking. For each rapid current change of great magnitude there are two sparking intervals in a commutating pole motor and only one in a non-commutating pole machine.

One sentence in the paper reads " and the recently developed type of controllers provides special protection against unnecessarily severe conditions being imposed on the motors." These controllers protect both commutating pole and non-commutating pole motors against unnecessarily severe conditions. If the controller does it, why not omit the commutating pole entirely, and have a somewhat simpler machine? The author states that the torque of an a-c. mill motor is greatly dependent upon proper adjustment of resistances, while the torque of a d-c. motor is more independent of resistance adjustment. He then goes on to state that " these inherent features " of the a-c. mill motors protect the driven machines and the driving motor. It would seem more appropriate to state that " these inherent features " of the a-c. mill motors are so troublesome as to recommend the abandonment of the a-c. mill motor, a conclusion which at least one steel mill has almost arrived at.

Gano Dunn: The Standardization Rules, and, in fact, the standardization methods in all countries, are in need of a definition of what the relation of the root-mean-square to the real capacity of an intermittently used motor is.

The methods at present in use for rating intermittent service motors, as Mr. Whiting very properly pointed out, do not take directly into account the heat-absorptive capacity of the motor, nor do they take into account many other things, and, as he has said, the accuracy of applying the r.m.s. method really depends upon the shape of the efficiency curve of the particular motor in question, not to mention the motor's absorptive capacity and several other factors which might be named.

When, in the early history of the Standardization Rules, the question was up of a simple way of determining, artificially, if you will, the efficiency of generators, the rules incorporated methods which, while not entirely accurate, were so simple that they became universally employed, such, for instance, as measuring the no-load losses and then arriving by calculation at the resistance and other losses, making a result that was partly calculated and partly measured.

Now, just this kind of thing is needed in the case of intermittent service motors. Mr. Whiting's discussion contributes a good deal in that direction. For instance, if we could adopt some standard type of efficiency curve, and assume it to apply to all intermittent service motors, and then make such modifications in the r.m.s. rule as would cause that rule to be applicable to that particular type of efficiency curve, we would have secured an approximation that would undoubtedly be sufficiently close for all purposes, and would enable us to discuss intermittent service motors more intelligently than we now do.

We ought then to add to any ratings arrived at by that method, a factor representing the absorptive capacity of the motor; so that, given what you might call the equivalent continuous load of a motor, or given its cycle in intermittent service, and stipulating that the standard or arbitrarily adopted efficiency curve for heating shall apply to calculations in connection with this motor, we would have, by applying to these results the absorptive factor, a method by which we could compare a German motor with an American motor, or with motors made in any country, and by which we could compare motors of different manufacture in this country, even if their weight and absorptive capacity, and general characteristics, were very different.

If Mr. Wiley's paper and the discussion of it can stimulate the development of a method of arriving at some arbitrary basis of comparison between intermittent service motors better than the r.m.s. method, taking into account the absorptive capacity of the motors for heat, it will have done a great service.

F. R. Fishback: Mr. Wiley has given some tables in his paper, and I get the general impression that he believes alternating current should be used for auxiliary drives. The principle argument in favor of the a-c. motor is the question of line transmission and commutator troubles, the big bugbear of all our troubles. With commutators designed to take care of the present-day loads, we can neglect the commutator question. In the table referred to, Mr. Wiley states that during a period of a year, and covering a large number of motors, no new commutators were put on, no new shafts were required and only 10 new sets of armature coils. Six of these were for 25-h.p. motors and four for 50-h.p. motors. The total repairs, according to the table, have been purely a question of armature coils. I think it is also safe to assume that in the list of motors taken, a large per cent of the motors were controlled with the manual controllers. I say this because it has not been common practise until recently to put automatic controllers on motors of 50 h.p. or under. With automatic control on all of the motors in the table above, the number of new armature coils required could have been greatly reduced, if not eliminated.

There is also the question of the electric brake that enters into the question of repairs on a motor. The d-c. brake is a much simpler one than the a-c. brake. A long-stroke plunger can be used, and this gives plenty of leeway and clearance in designing the brake. The d-c. brake consists of a steel casting, a winding and a steel plunger. The a-c. brake has a short-stroke plunger and is made up of laminated pieces, which chatter and easily get out of order.

The d-c. motor is the only right motor for auxiliary drive. The d-c. motor has the advantage over the a-c. motor of speed control and dynamic braking, and the most important advantage of all in that it will lift above its capacity until it burns out. This characteristic of the d-c. motor is most important in steel mill work where it is often cheaper to burn out an armature rather than wreck a more expensive machine or kill a man.

A. G. Ahrens: In connection with Mr. Treat's criticism of the commutating pole motor, that it is not able to stand heavy overloads of torque, I do not think Mr. Treat had in mind the mill motor. Mr. Lanier pointed out that the mill motor on ordinary loads is under-commutated, so to speak, so that on extreme overloads it is found that it commutates at its best. I have seen mill motors under a test with the special object of obtaining data as to their commutating ability, and I remember one test in which the motor was rated at 25 h.p., mill rating, which is equivalent to an armature current of 113 amperes, and under 400 amperes load, which is equivalent to over 350 per cent of normal load, that motor was sparking slightly, a condition of commutation which would have been called good on any industrial motor.

Brent Wiley: In regard to Mr. Whiting's question concerning reduced voltage, this subject has been considered from the standpoint of average conditions for motors operating with widely and rapidly fluctuating loads. This average condition is assumed to be such that the average voltage during the entire day, where 24-hour service is required, is one-half normal line voltage. For example, if the normal line voltage is 230 volts, the average voltage is figured at 115 volts for a cycle in which the motor is operating at full voltage approximately 40 per cent of the total time; and the heating of the motor is calculated on the basis of the equivalent continuous current at this reduced voltage. Operation with reduced voltage at armature terminals, due to insertion of resistance in series, for a greater percentage of time, would give equivalent results.

For a large majority of the applications for which the mill motor is particularly suitable, it is practically impossible to predetermine the exact cycle of operation, including time and load. It has been determined, however, that by averaging the data and conditions for various installations in steel mills, the actual operating period of the motor is approximately 40 per cent of the total period, and the table of ratings given has been developed on the basis of average voltage at the motor terminals equal to one-half normal line voltage.

It would be of advantage to take the motor characteristics into consideration when calculating the heating effect of a varying load for those cases where the load curve can be predetermined accurately; and further investigation of this point would be of value. It is questionable, however, if the attempt to apply such a close theoretical analysis would be of practical value for the general application of mill type motors.

Mr. Treat has questioned the ability of the commutating-pole mill motor to meet successfully the severe conditions of steel mill work.

The particular function of the commutating pole feature is to give better commutation over a wider range of operating conditions than can be obtained by the non-commutating pole motor. With the conditions to be met well established, there are no reasons why the proper commutating pole features cannot be included and better results obtained. It is true that, until a comparatively recent period, the theory of commutating pole design was not well established, and its application to motor design was therefore somewhat limited; but the unqualified success of the commutating pole railway motor is a forceful demonstration that for even severe, intermittent and widely varying load conditions, commutating poles are of great advantage.

Mr. Treat's criticism of the commutating pole motor for use in heavy-duty reversing service seems to be based on some particular design. It has come to be recognized that motors must be designed especially for this service, electrically as well as mechanically. No one conversant with conditions would apply a motor in this service having the same mechanical design as a motor suitable for, say, printing press drive. It is important to have a liberal electrical design and the use of the commutating pole permits this without going to proportions of armature that would make the machine excessively large. It is perfectly practicable to so proportion motors of the largest sizes required in this service that they will commutate the heavy overloads sparklessly, at the same time giving sparkless commutation on full load and lighter loads.

The time lag referred to between the current inrush and the building up of the flux is very much less than might be supposed, since the ampere-turns on the pole are ample to force the flux, not only through the pole, but also through the gap. As the ampere-turns required for the gap are many times those required for the iron part of the circuit, there is a very high m.m.f. forcing the rapid building up of the flux.

Results actually secured with commutating pole motors in this service show that no injurious results follow from this very slight time lag.

There are many applications of the commutating-pole mill motor being made on the mill machinery referred to by Mr. Treat, and from the preliminary tests that have been made, improved commutating conditions, as compared with those obtained with the older types of non-commutating pole motors, can be assured.

The reference which was made in my paper to improvements in control apparatus has a more significant meaning than has been brought out in the discussion. The point is that these improved conditions make it possible in many cases to increase the working capacity of the motor by the use of commutating poles. The function of series relays and series switches is to limit the accelerating and braking current to a predetermined amount. In the majority of applications, rapid acceleration and retardation are desirable—limited, however, to such values as are necessary to protect machinery and motor. With commutating pole motors these values of the current will be more dependent on the limits imposed by the machinery rather than by the motor. As the commutation limit has been raised, it means that the working capacity of the motor has been raised. It becomes more a question of heating limitations and, as stated previously, fireproof windings permit a much higher safe rise of temperature than can be obtained with the older types of motors.

Regarding the question of the relative merits of the alternating-current and the direct-current mill motors, as mentioned by Mr. Treat and Mr. Fishback, this is a very broad subject and it is not within the scope of this paper to give the various points proper discussion. There is no doubt that, for the most severe service, such as screw drives and reversing tables, the direct-current series motor has more advantageous characteristics. This is equally true of the hoist motion of cranes; but the question whether one type of motor or the other should be used should not be answered on this basis alone. With the increased attention which is being given the question of economies, there is good reason to believe that the application of the alternating-current mill motor will be made in accordance with the saving that it will insure. Much progress has been made regarding the design of an alternating-current mill motor with suitable features for this severe duty, and a careful study of the gradual applications by the designing and the field engineer will insure further progress in the successful application of this type of motor.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 25, 1912.

ELECTRIC BRAKING OF INDUCTION MOTORS

BY H. C. SPECHT

For various classes of work—for cranes, hoists, rolling mills, etc.—it is generally required that means be provided for stopping the motor quickly. When the electric power supply to the motor is taken off, the motor speed will gradually slow down, due to the friction load; however, the time required to bring the motor to a standstill by this method is generally too long, and other means have to be applied, stopping by brakes mechanically, electrically, or hand-operated, electric braking by alternating or direct current, etc.

The object of this paper is to discuss electric braking by alternating current and by direct current. If the braking is to be effected by alternating current, it is necessary to reverse the rotating field in the motor. This is ordinarily done on a three-phase motor by reversing two of the primary leads, and on a two-phase motor by reversing the two primary leads of one phase. At the moment of reversal, if the motor is running very near synchronous speed, a frequency is obtained in the secondary approximately twice that of the primary, because the secondary frequency is equal to primary frequency multiplied by the slip, which in this case is approximately two. Further, the secondary voltage changes in the same ratio as the secondary frequency, therefore, if the secondary is running with double frequency, the secondary voltage will be twice the voltage at standstill. This necessitates either that the secondary winding be insulated for the double voltage or that only half voltage be supplied to the primary for braking. On small machines the secondary voltage at standstill is so low that the insulation is strong enough to withstand the double voltage under the required operating conditions.

On large slip ring motors, however, the secondary has to be designed for rather high voltage, in order to avoid too high currents. A higher voltage requires more insulation, while a greater current requires larger and more expensive switches, heavier leads and larger collector, etc. In order to meet the best conditions, it is necessary to make a fair compromise between the above advantages and disadvantages.

If the rotor is star-wound, the voltage to ground can be reduced by grounding the neutral point, thus allowing a decrease of insulation to ground. However, the insulation between phases cannot be reduced, because the voltage between phases does not change by grounding the neutral point.

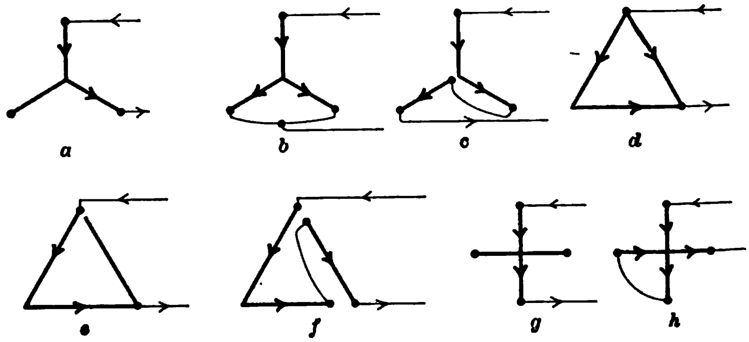


Fig. 1

On very large motors, of several thousand horse power, it sometimes becomes more desirable to apply half voltage to the primary or to use direct current for braking. In the case of application of half voltage to the primary, auto-transformers and extra switches are required, which entails some extra expense and complication. The braking by direct current may be accomplished by connecting the direct-current supply circuit to the primary as shown in Figs. 1a, 1b, 1c, to 1h.

The connections of Fig. 1a for three-phase star, 1d for three-phase delta and 1g for two-phase, are generally used on account of their permitting the simplest switching. By using some of the other connections, a little can be gained in regard to the field form and to the least power requirement.

From the preceding, it is to be noted that there are various schemes for electric braking, and that in every case a thorough investigation should be made to see which of the methods will give the best proposition in regard to safety, simplicity, cost and other requirements.

Before the alternating-current braking versus direct-current braking is discussed, a simple method will be given for each of them, indicating how to work up the speed-torque and ampere-torque curves. These methods are not claimed to be entirely accurate but are close enough for the practical purpose for which they serve.

METHOD OF BRAKING INDUCTION MOTORS BY ALTERNATING CURRENT

If the secondary ohmic and inductive resistances are reduced to primary terms by multiplying the resistances by the squared ratio of primary to secondary turns, or by squared ratio of the primary to secondary voltage, the induction motor windings may be represented by the diagram of Fig. 2.

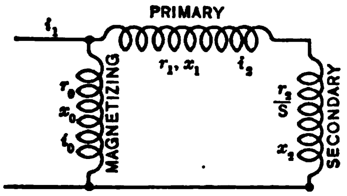


FIG. 2

The following notation is used:

e_1 = primary voltage between terminals.
e_2 = secondary " " "
i_1 = total primary amperes, equivalent to single-phase circuit.
(for three-phase $i_1 = \sqrt{3} \times$ terminal amperes.)
(" two- " $i_1 = 2 \times$ " "
i_0 = total no-load current.
i_2 = " secondary "
r_1 = primary ohmic resistance between terminals divided by 2.
r_2 = secondary " " " " " " 2.
x_1 = primary inductive " " " " " 2.
x_2 = secondary " " " " " " 2.
P_L = total watts with motor locked.
T = lb. torque at 1-ft. radius.
S = slip in decimals.
n_0 = revolutions per min. at synchronism.

Assuming that the primary current with motor locked is nearly in phase with the no-load current, then we may write

$$x_1 + x_2 = \frac{\sqrt{[(i_1 - i_0)\, e_1]^2 - P_L^2}}{(i_1 - i_0)^2} \qquad (1)$$

$$i_2 = \frac{e_1}{\sqrt{\left(r_1+\frac{r_2}{S}\right)^2+(x_1+x_2)^2}} \tag{2}$$

$$\text{h.p.} = \frac{i_2^2 \times (1-S) \times \frac{r_2}{S}}{746}$$

$$T = \frac{\text{h.p.} \times 5250}{n_0\,(1-S)}$$

These two formulas combined give

$$T = \frac{i_2^2 \times \frac{r_2}{S} \times 5250}{n_0 \times 746}$$

or

$$T = \frac{i_2^2 \times \frac{r_2}{S}}{n_0} \times 7.04 \tag{3}$$

$$S = \frac{i_2^2 \times r_2}{n_0 \times T} \times 7.04 \tag{4}$$

By introducing formula (2) into formula (3) and differentiating the new equation, it will be found that T is maximum when

$$r_1+\frac{r_2}{S} = x_1+x_2$$

Finally, the primary current i_1 is obtained by adding geometrically the magnetizing amperes to the secondary amperes i_2. Those who are familiar with the circle diagram will obtain the current i_1 very quickly from the diagram (see Fig. 3).

The points C_0 (no load) and C_L (locked) are determined by test or calculation. A vertical line in the center of C_0C_L will pass through the center of the circle. For the above purpose, it is accurate enough to draw another line through C_0 parallel to the base line, then the intersection with the vertical line on C_0C_L will be the center of the circle.

As found analytically, the value for i_1 (see Fig. 4) is as follows:

$$i_1 = \sqrt{\left[\frac{(x_1+x_2) \times i_2}{\sqrt{\left(r_1+\frac{r_2}{S}\right)^2+x_1+x_2)^2}}\right]^2 + \left[\frac{\left(r_1+\frac{r_2}{S}\right) \times i_2}{\sqrt{\left(r_1+\frac{r_2}{S}\right)^2+(x_1+x_2)^2}}\right]^2} \tag{5}$$

or

$$i_1 = \sqrt{(i_2 \times \sin\phi_2+i_0)^2+(i_2 \times \cos\phi_2)^2}$$

EXAMPLE

Motor. 2000-h.p., three-phase, 6600-volt, 25 cycles, 6-pole, star-wound, both primary and secondary.

The tested values for full voltage of 6600 on primary are:

i_0 = 58 amperes total; no-load watts = 32 kw.
i_L = 1550 amperes with motor locked.
P_L = 1950 kw. with motor locked.
r_1 = 0.38 ohms.
e_2 = 1700 volts.

The resistance of secondary winding per phase at 40 deg. cent. = 0.026 ohms; therefore the secondary resistance reduced to primary terms is

$$r_2 = 0.026 \times \left(\frac{6600}{1700}\right)^2 = 0.39 \text{ ohms}$$

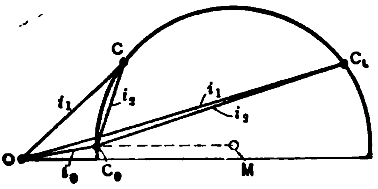


FIG. 3

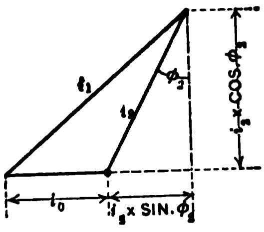


FIG. 4

In Fig. 5, for the different speed-torque curves 1 to 9, the secondary resistances reduced to primary turns have the following values:

Curve 1.	$r_2 =$ 0.39	ohms	without	external	resistance.
" 2.	$r_2 =$ 1.2	"	inclusive of	"	"
" 3.	$r_2 =$ 2.4	"	"	" "	"
" 4.	$r_2 =$ 5.0	"	"	" "	"
" 5.	$r_2 =$ 8.0	"	"	" "	"
" 6.	$r_2 =$ 13	"	"	" "	"
" 7.	$r_2 =$ 20	"	"	" "	"
" 8:	$r_2 =$ 34	"	"	" "	"
" 9.	$r_2 =$ 60	"	"	" "	"

According to formula (1)

$$x_1 + x_2 = \sqrt{\frac{[(1540-58) \times 6600]^2 - 1{,}950{,}000^2}{(1540-58)^2}} = 4.37 \text{ ohms}$$

For $r_2 = 0.39$ and $S = 2$

$$i_2 = \frac{6600}{\sqrt{\left(0.38+\frac{0.39}{2}\right)^2+4.37^2}} = 1496 \text{ amperes}$$

$$T = \frac{1496^2 \times \frac{0.39}{2}}{500} \times 7.04 = 6100 \text{ lb.}$$

Then for various slips from 2 to 0, the torque curve 1 and the secondary ampere curve are obtained as shown in Fig. 5.

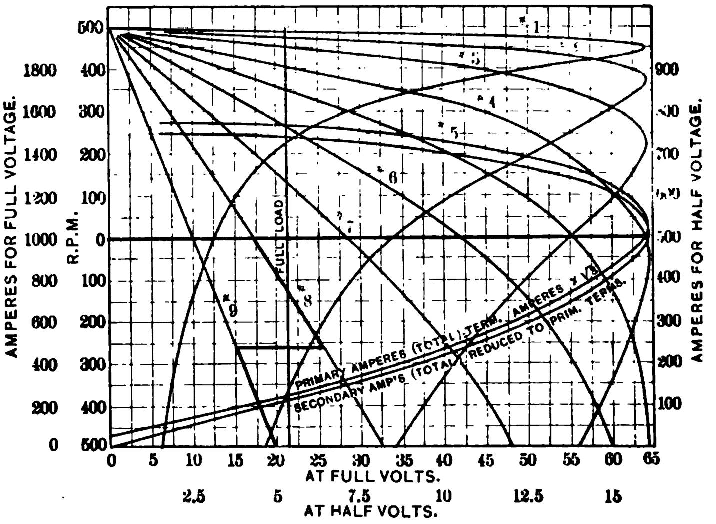


FIG. 5—AMPERE, SPEED-TORQUE CURVES FOR A-C. EXCITATION

After the ampere curve for one speed-torque curve is determined, the torque curves for the various values of r_2 with external resistance can be figured quickly according to formula (4). The primary amperes may be obtained either from diagram or may be calculated according to formula (5). It should be noted that the amperes plotted in Fig. 5 are total and not terminal amperes. In order to obtain terminal amperes, the values should be divided by $\sqrt{3}$.

The torque curves above the zero base line (Fig. 5) represent the motive torque curves, and those below the zero line, the braking torque curves. All these curves have the ampere curve in common, its lower branch corresponding to the upper branch of the speed-torque curves, and the upper branch of the ampere curve corresponding to the branch of speed-torque curves below the maximum torque, or pull-out point.

Further, it may be noted that for the most effective braking and with the least amount of current, a variation of resistance in the secondary is required. If, for instance, the motor should be stopped with a torque equal to average full load torque, and a current not greatly exceeding the full load current, the resistance should be decreased step by step until the motor stops. This is demonstrated in Fig. 5 by the heavy zigzag line. If a liquid rheostat is used instead of metallic resistance, it would be possible to change the resistance in such a manner that the torque and amperes would remain practically constant during the whole braking period. It is also obvious that unless reversal of the motor is wanted, the primary supply circuit has to be disconnected as soon as the motor comes to rest.

In the foregoing example the braking was based on applying full voltage to the primary, and it may be of interest to know how the curves will change if lower voltage is used for the braking. Since the ohmic as well as the inductive resistance remains unchanged, it is clear that the currents vary in the same ratio as the voltage, and that the torque changes with the square of the voltage or amperes. Therefore, the same curves which have been worked up for full voltage can also be used for lower voltages, simply by changing the ampere scale in the ratio of the voltage change and the torque scale by the squared ratio of the voltage change. This is done in Fig. 5 for half voltage.

Finally, it can be seen from Fig. 5 and formula (3) that for half the secondary resistance and the same current as for full voltage, the torque is reduced only to half the full-voltage torque value. Therefore, in order to brake the motor at half voltage with full-load current and half the full-load torque, the secondary resistance must be half that at full voltage. This torque, however, can be obtained only when the motor has at full voltage a maximum torque, or pull-out torque, of at least twice the full-load torque, because the maximum torque at half voltage will be only one-quarter of that at full voltage.

If the motor has a squirrel-cage rotor, it is obvious that only one speed-torque curve can be obtained, due to the fixed resistance in the secondary, and in order to obtain a good torque for braking, starting, or reversing, without an excessive current, the secondary winding must have a high resistance. Consequently this kind of motor is very inefficient under running conditions, due to the high secondary ohmic drop, and should, therefore, be applied only for very intermittent service, for elevators, cranes, hoist or similar work.

METHOD OF BRAKING INDUCTION MOTORS BY DIRECT CURRENT

The following notation is used:

r_2 = secondary ohmic resistance measured between terminals and divided by 2.
x = inductive resistance at synchronism.
S = slip in decimals ($S = 0$ at synchronous speed of motor).
($S = 1$ " standstill).
n_0 = revolutions per min. at synchronism.
n = " " " " which motor runs.
e_2 = secondary voltage between terminals at no-load speed.
i_2 = total secondary current equivalent to single-phase.
(For three-phase i_2 = terminal amperes $\times \sqrt{3}$)
" two- " i_2 = " " $\times$ 2)
i_s = total secondary short-circuit current for inductive resistance only.
i_1 = total primary amperes.
T = torque in lb. at 1-ft. radius.
i_0 = direct current for exciting.
t_1 = number of turns per phase in primary.
t_2 = " " " " " " secondary.

For the direct current for exciting, an alternating current can be substituted, having a value of $\frac{1}{\sqrt{2}}$ times the direct current, and then, for synchronous speed, the voltage and short-circuit current in the secondary can be determined by transformation. The short-circuit current is equal to the equivalent alternating magnetizing current, reduced to the secondary turns. The secondary open-circuit voltage obtained by alternating-current excitation at standstill is the same as that obtained by the equivalent direct-current excitation when running at synchronism. However, in determining the corresponding alternating short-circuit current, the distribution and the amount of winding which is excited by direct current has to be taken into consideration, *i.e.*, the current must be multiplied by another factor (C) besides $\frac{1}{\sqrt{2}}$. For example, the factor C for a three-phase winding of which two of the phases are excited by direct current (see Figs. 1a and 1e) is equal to 1.15.

According to the foregoing, the total short-circuit current in a three-phase secondary at synchronism which would be obtained if the rotor had inductive resistance only, and no ohmic resistance, is

$$i_s = \frac{i_0 \sqrt{3}}{\sqrt{2}} \times \frac{t_1}{t_2} \times C \tag{6}$$

and the equivalent primary alternating current is

$$\left.\begin{aligned} i_1 &= \frac{i_0 \sqrt{3}}{\sqrt{2}} \times C \text{ for three-phase primary} \\ i_1 &= \frac{i_0 \, 2}{\sqrt{2}} \times C \text{ `` two- `` `` } \end{aligned}\right\} \tag{7}$$

After having determined the primary current, the corresponding secondary voltage e_2 can be read off on the open alternating-current saturation curve, or in case neither the alternating-current nor the direct-current saturation curve is available, the secondary voltage can easily be calculated.

After having determined the secondary short-circuit current and the open-circuit secondary voltage e_2, the inductive resistance x is found by

$$x = \frac{e_2}{i_s} \tag{8}$$

Finally, the secondary current and torque for various secondary resistances and slips are given approximately by

$$i_2 = \frac{e_2}{\sqrt{\left(\frac{r_2}{S}\right)^2 + x^2}} \tag{9}$$

$$T = \frac{i_2^2 \, r_2}{n} \times 7.04 \tag{10}$$

or

$$S = \frac{n_0 \, T}{i_2^2 \, r_2} \times 7.04 \tag{11}$$

By substituting the value of i_2 of formula (9) in formula (10) and differentiating this new equation, it will be found that the maximum torque is always attained when $\frac{r_2}{S} = x$

EXAMPLE

In order to obtain a comparison between alternating-current and direct-current braking the same 2000-h.p. motor is selected for example.

Assuming that the primary is excited by direct current across two terminals of the star winding and that this current is 100 amperes, then, according to formulas (6) and (7)

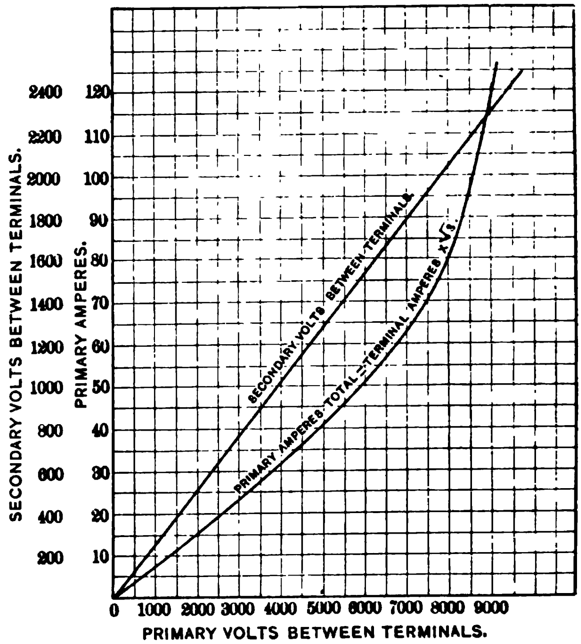


FIG. 6—SATURATION CURVES FOR A-C. EXCITATION
Motor standing still, secondary open-circuited

$$i_s = \frac{100\sqrt{3}}{\sqrt{2}} \times \frac{6600}{1700} \times 1.15 = 550 \text{ amperes total}$$

$$i_1 = \frac{100\sqrt{3}}{\sqrt{2}} \times 1.15 = 141.7 \text{ amperes total}$$

The corresponding secondary voltage e_2 for this current $i_1 = 141.7$ is found from the saturation curve of Fig. 6.

$$e_2 = 2420 \text{ volts}$$

Then the inductive resistance x is equal to

$$x=\frac{2420}{550}=4.4 \text{ ohms}$$

For the various secondary resistances r_2, the following values are selected: (see Fig. 7)

Curve 1. $r_2=0.026$ ohms without external resistance.
" 2. $r_2=0.5$ " including " "
" 3. $r_2=1.0$ " " "
" 4. $r_2=2.0$ " " " "
" 5. $r_2=3.0$ " " " "

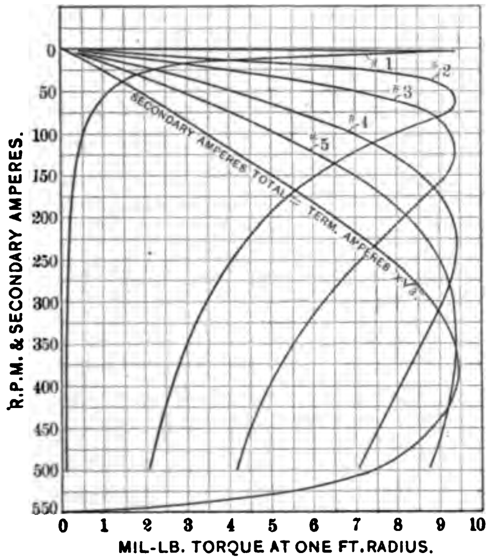


FIG. 7—AMPERE, SPEED-TORQUE CURVES
For direct-current excitation of 100 amperes.

For $S=1$ and $r_2=0.5$ ohms, the secondary current i_2 and torque T are

$$i_2=\frac{2420}{\sqrt{\left(\frac{0.5}{1}\right)^2+4.4^2}}=548 \text{ amperes}$$

$$T=\frac{548^2\times0.5}{500}\times7.04=2120 \text{ lb.}$$

Then in the same manner the currents and torques for other slips and resistances may be figured, and in Fig. 7 the results are shown. It will be noted that the different speed-torque curves have the ampere curve in common, as in the case of braking with alternating current.

Curve 1 (without external resistances) shows that the torque at 500 revolutions per minute is nearly zero and increases very slowly as the speed decreases, except that below 50 revolutions per minute the torque increases much faster. At about three revolutions per minute the torque reaches almost instantly the maximum value of 9400 lb. (4260 kg.) and from then on until standstill the torque drops very rapidly to zero value. Therefore, this speed-torque curve is of no practical value, and in order to obtain good braking torque over a wider range of speed it is necessary to insert a fairly large resistance.

Further, the curves in Fig. 7 show that the maximum torque obtainable with an exciting current of 100 amperes is not even quite half the full-load torque, and that the open-circuit secondary voltage at synchronism is 42 per cent greater than the voltage at standstill with 6600 volts (alternating current) on the primary.

A greater torque could be obtained by increasing the exciting current, which, however, would give a still higher secondary voltage and a stronger field, thus increasing the inevitable unbalanced pull and the danger of greater potential rise in case any of the circuits should break. The conditions for direct-current braking of this particular motor are very poor, because the magnetizing or no-load alternating current is so very small compared to the full load current. However, most of the induction motors have a comparatively greater no-load current and consequently give more favorable results than in the case of this 2000-h.p. motor. Nevertheless, without running too great a risk in regard to high secondary voltage and great unbalanced pull, the very best torque which can ordinarily be obtained by braking with direct-current is not greater than full-load torque.

As a check on the foregoing results for the secondary voltage e_2 and short-circuit current i_s, the same motor was driven by another motor at synchronous speed, the primary was excited by direct current and the open-circuit secondary voltage measured. Then the secondary circuit was closed and short-circuit amperes measured. The results are shown in Fig. 8. Curves 1 and 3 in this figure correspond to an excitation of two phases, according to connection of Fig. 1a, and curves 2, 4 and 5 correspond to excitation of all three phases, according to connection of Fig. 1c.

Curve 5 represents the saturation which is obtained by having two of the secondary terminals short-circuited and the voltage measured across the terminal of the open phase and one of the short-circuited phase terminals. It is to be noted that this gives an increase in voltage of approximately 25 per cent over the saturation curve (4) with all three phases in the secondary open-circuited.

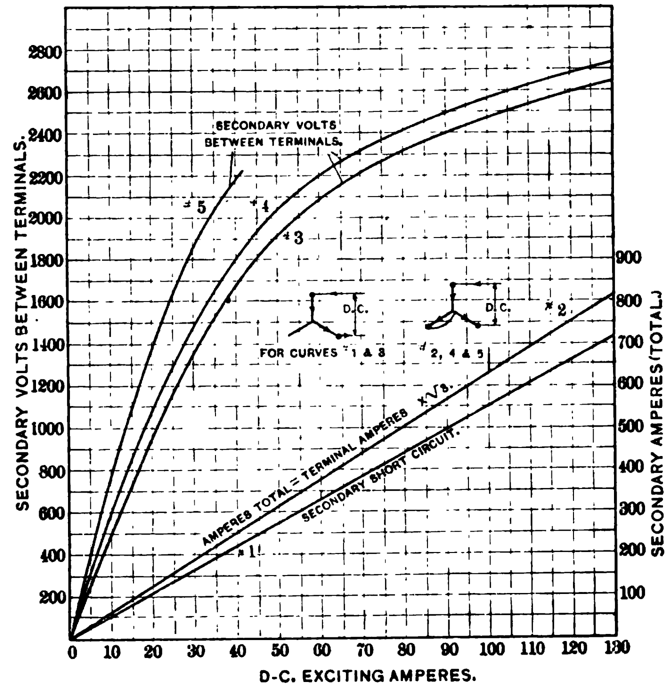


Fig. 8—Saturation Curves, with Direct-Current Excitation

Comparing now the results of the direct-current braking with those of the alternating-current braking, the following may be said:

1. The braking torque obtainable by alternating current, even with only half the primary voltage, is, as a rule, considerably greater than with direct current.

2. In braking with alternating current, the line circuit has to be taken off from the motor as soon as the motor comes to a

stop, otherwise the motor will reverse, whereas in braking with direct current the motor comes to rest only, and will not reverse whether the excitation is taken off the motor or not.

3. With alternating current, it is an easy matter to brake the motor with a strong and practically constant torque during the whole period of stopping, whereas with direct-current excitation it is somewhat difficult to obtain good braking torque near standstill due to the rapid decrease in torque from maximum to zero, because, no matter how great the direct exciting current is at standstill, no torque can be developed.

4. If it is desired to brake the motor with full-load torque by means of direct current, the secondary voltage at synchronism will not be far from double voltage, which is the same value that would be obtained by braking the motor with alternating current at full primary voltage.

5. Since the magnetic field for direct-current braking has to be much stronger than for alternating-current braking, the danger of serious potential rise, due to breaking of any of the circuits, is greater with direct-current excitation than with alternating current.

6. For the same reason given in the foregoing paragraph, the danger of heavy unbalanced pull is greater with direct current than with alternating current.

7. The only great advantage of braking with direct current is the small electric energy which is needed. Only the I^2R losses of the primary are to be supplied when direct current is used, while with alternating current the full power has to be supplied that the motor would require for developing an equal torque at normal operating condition.

From the foregoing, it is obvious that in cases where infrequent braking is called for, braking by alternating current has, as a rule, preference over the direct-current braking method. However, in cases, as on hoists, cranes, etc., where very frequent braking takes place, the direct current may be preferable on account of saving in power.

DISCUSSION ON "ELECTRIC BRAKING OF INDUCTION MOTORS" (SPECHT), PITTSBURGH, PA., APRIL 25, 1912.

H. E. White: I have been greatly impressed with one particular point to which I think attention should be called, that is, it is impossible to consider the induction motor, or the direct-current motor, by itself alone. Mr. Specht's paper shows clearly what can be done in using an induction motor with electric braking, but it would appear that the admission must be made that after all it is not an electric braking, but a reverse power system which is described. I recall one application where this was tried. The hoist did not always attain full speed, at least not in the preliminary test, and after coming to rest, would reverse without coming to rest at the point where the automatic devices that had been provided should have stopped it.

Several times I tried to find out what could be done by applying direct current to the primaries of induction motors. I know of one successful case—it happened to be a very high voltage motor. However, if you take a motor of the voltage that is favored in steel mill work, 220 volts, it will be found that the direct-current voltage, applied directly to the terminals, which will give a good braking effect, will be found to be a very low voltage, only 3 or 4 volts in some cases.

It should be brought out prominently in this connection that the direct-current motor possesses possibilities of control that the alternating-current motor does not possess, and with the advent of the series contactor this difference in favor of the direct-current motor seems to be very greatly increased. The designers of the motor generally will neglect to consider the problem of controlling it. The time has come when both must be considered together, and nothing can be considered by itself.

H. F. Stratton: Mr. Specht, in his comparisons of the relative merits of dynamic braking with direct-current and alternating-current excitation, says that with the direct-current excitation only a weak braking torque can be developed near standstill, and he would have us believe that, at the instant standstill is reached, the braking torque becomes nil. This would be equivalent to saying that dynamic braking on direct-current motors becomes very small at the time the speed of rotation has reached practically zero, and certainly does not persist at all at standstill. While this statement appears plausible from an academic standpoint, it is, as a matter of fact, not true. The dynamic braking current does exist for an appreciable length of time after the motor has stopped, owing to the desire of the braking current to keep flowing in the same direction; in other words, this is an induction effect. We have had come to our attention motors driving cranes, which actually caused the wheels to skid upon the application of dynamic braking ***after the motor has come to rest.*** The motor was absolutely locked stationary by the dynamic braking current while the crane skidded a distance of several inches.

Gano Dunn: I should like to give a little matter along the line of Mr. Stratton's talk, in respect to having worked with the principle he mentioned, only to a greater extent, a number of years ago. The real situation is one in which there is resonance between the magnetically stored energy, on the one hand, and the mechanically stored energy on the other. They are, as you might say, in a different phase, and when I was conducting these experiments it was not at all unusual to see, when a proper relation had been arranged between the braking resistance and the inductance in the braking circuit, the motor not only brought completely to rest, but started running backwards in many cases very rapidly. It is perfectly possible, in other words, for advantage of this phenomenon to be taken to further braking schemes of all kinds.

An interesting experiment may be made in connection with little hoist motors which brake by short-circuiting through a certain fixed resistance. I have seen that resistance so adjusted that one would think a metal bar had been put through the spokes of the pulley and suddenly withdrawn, so violent was the stoppage, and so elastic was the spring back, that for a moment you did not know that the motor had been stopped at all, since you finally saw it come to rest, after running in the opposite direction.

I believe there is no equivalent for this in connection with the alternating-current braking that Mr. Specht has brought out, because, as has been pointed out, that is really reverse power braking, but the current braking that I have been referring to is really a balancing of stored magnetic energy on the one hand, against stored mechanical energy on the other hand, which takes place when there is a suitable adjustment between the amount of inductance and the amount of resistance. It is capable of very useful employment.

John C. Reed: The possibility of extracting the energy from a moving mass by means of dynamic braking has become quite common, but I do not remember ever to have heard or read any discussion as to the possibility of stopping the mass and then extracting the energy. It is my belief, however, that this can be and is being done. I am familiar with an elevator used in connection with a blast furnace where I believe this is being done. The elevator referred to is not a skip hoist, but a straight vertical lift, and anyone can readily appreciate the difference, since a skip need only be stopped within a limit of five or six inches, while in a straight lift the floor of the cage must come flush with the top floor, since if it is one-fourth inch too low it is difficult to remove the heavy buggies from the cage, while if it is one-fourth inch too high it is difficult to put them back on again; more than one-fourth inch is not allowed.

If the weight of the load on the elevator never varied it might be possible to set the cut-off so that the drift would always bring the floors level, but since the weights vary as much as a hundred per cent, satisfactory operation cannot be accomplished in this way, because the cage will run high or low, depending upon whether the load is less or more than that for which the cut-off is set. This trouble was overcome by short-circuiting the armature an instant following the cutting off of the current. This apparently stops the elevator instantly and all the brake has to do is to hold the load. I am not prepared to say whether the dissipation of the energy contained in the moving mass which must take place within the motor, occurs immediately preceding or immediately following the stoppage, but I am inclined to believe that some of it follows the stoppage.

Clark S. Lankton: I would like to mention one instance of alternating-current braking which is working satisfactorily. The motor is a 1200-h.p. induction motor working in conjunction with a heavy flywheel. The transformers feeding the motor are delta-connected and two transformers have a central tap, whereby half voltage is obtained with an open delta connection. By means of a double-pole double-throw switch this half voltage can be applied in the reverse direction, thereby establishing an effective plug. Three to four minutes are ordinarily required to stop against the friction of the roll train, but with the plug only thirty-five seconds are necessary.

H. C. Specht: Mr. Lankton told us, as I understand from him, that the alternating-current braking, with the flywheel on the motor, takes from three to four minutes to stop. This is rather a long time for braking. It is generally possible to brake almost any induction motor with a flywheel connected to it, inside of 10 seconds, if there is a proper resistance in the circuit and full voltage applied to the primary. However, on motor-generator sets, particularly of higher speeds, the time of stopping will be considerably longer.

C. S. Lankton: The flywheel was directly connected with the motor all the time. Ordinarily the motor would run, with the flywheel connected, approximately from three to four minutes, but by putting on half voltage V-connected plug, the motor would stop in about 35 seconds.

Gano Dunn: I believe if this were a case of certain flywheels being brought down in ten seconds, the title of the paper ought to be what by a misprint it actually was when the first copies came from the printer, " Electric Breaking of Induction Motors."

C. S. Lankton: Even with the half voltage, we get about a load and a quarter in amperes on the motor. I think it would be very severe to stop it in 10 seconds.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 26, 1912.

ELECTRIFICATION OF A REVERSING MILL OF THE ALGOMA STEEL COMPANY

BY BRADLEY T. MCCORMICK

GENERAL DESCRIPTION

The Algoma Steel Company of Sault Ste. Marie, Ont., Canada, has recently put into operation an electric reversing mill equipment operating the blooming mill. The mill is required to roll 75 tons per hour from ingots 20 in. (50 cm.) by 20 in. (50 cm.) into billets 8 in. (20 cm.) by 8 in. (20 cm.) in 15 passes.

The electrical equipment (see Fig. 1) is in a separate building from the mill, with an opening in the wall to permit connection between the mill motors and the rolls, while in the mill room, in a position convenient to the operator, are placed the operating controller and an instrument column carrying meters showing the current, voltage, and speed of machines.

The rolls are driven by two 600-volt direct-current motors mounted on the same shaft. Each of these motors has a normal rating of 2000 h.p. at 75 rev. per min., and their armatures are connected in series across 1200 volts. The current for the motors is supplied by a flywheel motor-generator set consisting of two 1700-kw. 600-volt direct-current generators, with their armatures also connected in series, driven by a 25-cycle, three-phase induction motor of 1800 h.p. capacity, at 375 rev. per min. synchronous speed. A 150,000-lb. (68,000-kg.) flywheel serves to equalize the load, so that the power drawn from a 25-cycle line is kept practically constant at a value corresponding to the average power required by the rolling mill motors. An idea of the construction of the flywheel motor-generator set can be gained by reference to Fig. 3.

As the power demand at the rolls rises and falls, a slip regulator automatically inserts or cuts out resistance in the rotor circuit of the induction motor, thus providing sufficient speed variation of the motor-generator set to enable the flywheel to alternately deliver and absorb energy in such a way as to make the load on the 25-cycle power line practically uniform. When the power demand of the roll motors exceeds the average, the resistance in the rotor of the induction motor is increased. This decreases the speed of the motor-generator set, preventing a rush

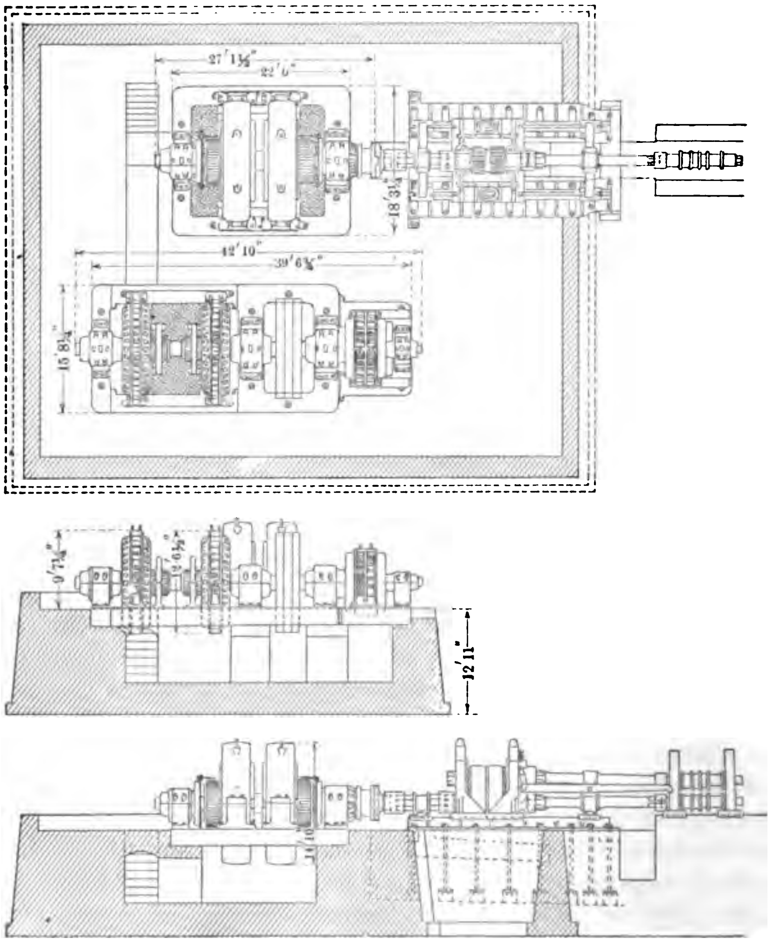


Fig 1—Rolling Mill Equipment

of current from the alternating-current line, and at the same time allowing the flywheel to give up part of its stored energy to carry the mill motors over the peak load. When the power demand is light, the resistance is cut out of the rotor circuit, allowing the induction motor to speed up the set and store energy in the flywheel.

From the foundation plan it will be noted that under both the motor-generator set and the mill motors pits are provided in order to give easy access to the underside of the machines where the leads are connected to the terminal boards. These pits also provide a place for locating series shunts, resistances, etc., which would be very unsightly if placed above ground. The opening under the motor-generator set is connected to the one beneath the motor by a passage way, and is reached by a stairway leading from the main floor.

The speed control and the reversal of the mill motors are effected by varying the voltage impressed upon their armatures, through rheostatic control of the fields of the generators.

The excitation for both the mill motors and the generators is supplied by a 40-kw. 250-volt induction motor-generator set. Fig. 8 shows the complete connection diagram for the equipment. The direct-current circuit is protected by a relay in series with the armatures of the generators and mill motors. When the current exceeds the setting of the relay, the latter opens an auxiliary circuit, tripping the circuit breaker in the field of the 40-kw. exciter, thereby killing the excitation on all the direct-current machines.

MILL MOTORS

Since the requirements of a motor drive for a reversing mill demand frequent reversals from full speed in one direction to full speed in the opposite direction in a very short space of time, it is of the utmost importance that the moving parts should be so designed as to obtain the minimum amount of inertia. To accomplish this result, the rolling mill drive was divided into two units, as shown in Fig. 2, mounted side by side on the same shaft and base. Each unit has a normal rating of 2000 h.p. at 600 volts and 75 rev. per min., with a maximum rating of 2½ times normal, giving a total maximum of 10,000 h.p. available at the rolls for short intervals. This corresponds to a maximum torque of 700,000 pounds (317,500 kg.) at one-foot (30.48 cm.) radius.

The motors have 16 poles and are of the commutating-pole type. They are also provided with compensating windings in the pole faces of the main poles, in order to reduce the distorting effect of the armature reaction upon the field which would otherwise become quite marked on the peak loads. The yokes are of cast iron, while the main poles and commutating poles are of laminated steel punchings. The fields are wound of strip copper on edge in two layers, with a duct between to afford an air passage for ventilation. Fig. 4, reproduced from a photograph of the lower half of one of the motor yokes, taken during the process of assembling, shows the construction of the fields. The fields are each separately excited from the 250-volt exciter mains, while a regulating resistance in series with each field circuit gives an adjustment by which the motors may be made to divide their load equally, in case of any slight difference which may exist between the saturation curves of the two machines.

The motor armatures are connected in series and are designed for a normal pressure of 600 volts, but by varying the value and direction of voltage impressed across the armatures, the motors can be made to run in either direction at any speed up to 75 rev. per min.

In order to withstand the severe mechanical stresses set up by the rapid reversals of rotation and the shocks transmitted from the rolls, it was necessary to make the spider and commutator of the most rigid construction. The bearings are protected from end thrust by a thrust collar mounted on the bearing pedestal next to the rolls (see Fig. 7). One side of the collar is of babbitt and the other of steel. Grease is used for lubricating and is fed by compression grease cups.

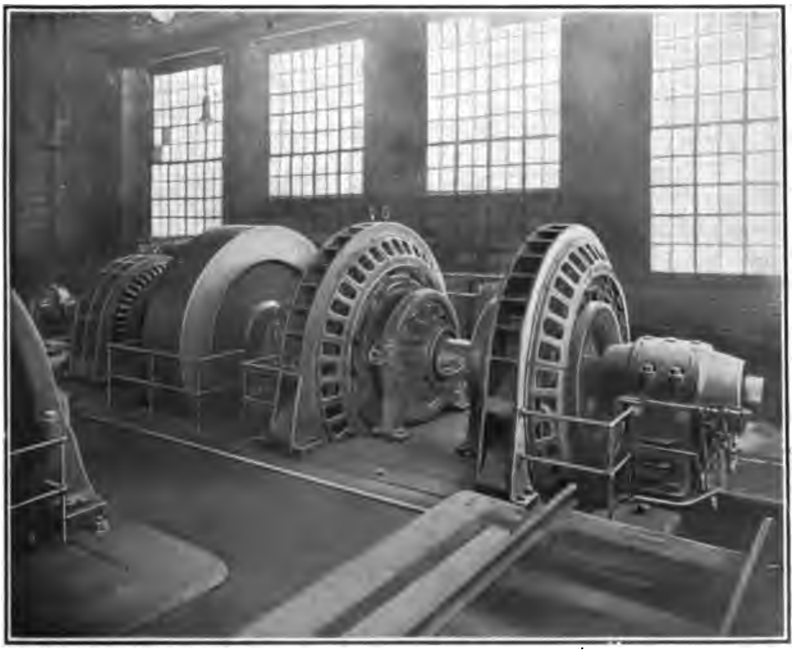
DIRECT-CURRENT GENERATORS

The generators each have a normal rating of 1700 kw. at 600 volts with a no-load speed of 375 rev. per min. The armatures are connected in series, giving 1200 volts across the two machines. They are capable of carrying an overload of 2½ times normal, corresponding to the overload of the mill motors. The generators are also of the compensated commutating-pole type, but the magnetic circuit is entirely of laminated steel, in order that the field may respond quickly to variations in excitation. Fig. 5 shows a portion of the generator during the process of construction.

The commutators are of the open neck type and are constructed in such a way that the air passes through the spiders of the machines, coming out through the commutator necks, and

[MC CORMICK]

FIG. 2—2000-H.P. MILL MOTOR

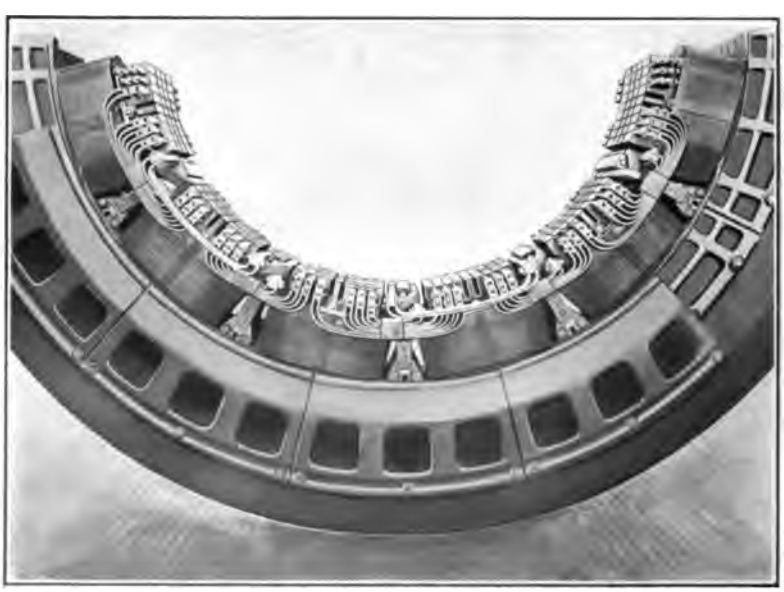


[MC CORMICK]

FIG. 3—FLYWHEEL MOTOR-GENERATOR SET

[MC CORMICK]

FIG. 4—2000-H.P. MOTOR UNDER CONSTRUCTION

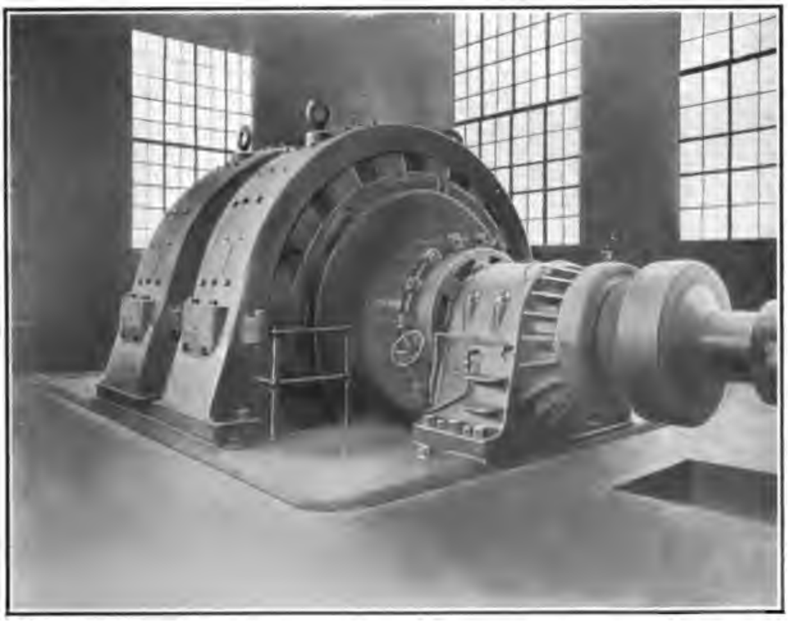


[MC CORMICK]

FIG. 5—1700-KW. GENERATOR UNDER CONSTRUCTION

[MC CORMICK]

FIG. 6—WATER-COOLED STARTING RESISTANCE



[MC CORMICK]

FIG. 7—2000-H.P. MILL MOTORS, SHOWING THRUST BEARING

blows across the face of the commutators. No other source of ventilation is necessary to cool the commutators. As any vibration of the brush rigging is very objectionable on commutators of such high peripheral speeds, the brush mechanism is supported on a separate yoke mounted on the base plate.

The fields of the two generators are connected in series and excited across the 250-volt exciter mains, and controlled by a rheostat of such construction that the excitation can be reversed and varied by small steps over any range between zero and the maximum. This rheostat is mounted in the mill room and is under the control of the man operating the rolls.

INDUCTION MOTOR AND FLYWHEEL

The induction motor has a rating of 1800 h.p., 2200 volts, three-phase, 25 cycles, at 375 rev. per min. synchronous speed. It is of the wound secondary type, in which the current from the secondary, or rotor, is carried out through slip rings to the slip regulator. As there is nothing special in the construction of the motor, it requires no further description. The flywheel is 12 feet (3.65 m.) in diameter, and is made of cast steel in three pieces, carefully machined on the rim and held together by fitted bolts passing through reamed holes.

BEARINGS AND LUBRICATION

It can readily be seen that the requirements of the bearings for the motor-generator set are somewhat more severe than are usually met with in electrical machines of the ordinary type. The heavy weight to be sustained by the bearings on either side of the flywheel requires considerable bearing surface, and necessitates a large bearing diameter with correspondingly high velocity of rubbing, in order that the bearings shall not be unreasonably long. The combination of high bearing pressure and peripheral speed requires the most careful design to secure perfect lubrication. All of the bearings, both on the motor-generator set and on the mill motors, are self-aligning, and provided with water cooling and three distinct methods of lubrication, ring oiling, oil flooding and pressure lubrication. Under ordinary running conditions the pressure lubrication can be dispensed with, but it is very useful in starting. When the motor-generator set comes to rest the oil film is squeezed out of the bearings, and unless this film can be established again before starting, a torque of about 60,000 lb. (27,200 kg.) at one-foot

(30.48 cm.) radius would be required to move the set from rest. But starting the oil pump soon establishes a film again so that the set will begin to revolve on the first step of resistance and come smoothly to full speed without any abnormal demand on the power station.

A small motor-driven oil pump furnishes the oil for both the flooded lubrication and pressure lubrication systems. The overflow from the bearings passes through a cooler and filter and then is pumped up into a storage tank, from which it flows by gravity into the bearings. Valves are provided so that the oil can be by-passed around the cooler, filter and storage tank, and be pumped direct into the bearings under pressure, when starting.

STARTING APPARATUS

The rotating parts of the motor-generator set revolving at 375 rev. per min. have a kinetic energy of 85,000,000 ft-lb. (11,755,000 kg-m.) During the period that the set is being brought to full speed, the resistance in the rotor circuit of the induction motor is required to absorb this amount of energy. In order to dispense with a bulky cast iron grid resistance, a special water-cooled resistance was used (see Fig. 6). This resistance consists of a boiler iron tank with a water inlet valve at the top connected to the water mains, and a quick-opening gate valve at the bottom for an outlet. The resistance element is immersed in water and consists of a hollow iron tube of helical form, with the taps for the various starting positions leading out through the top of the case. During the starting period the energy absorbed by the resistance is transferred to the water, after which the hot water can be emptied at the bottom and the tank refilled, ready for starting once more. The tank was designed with a water capacity sufficient to absorb 85,000,000 ft-lb. (11,755.000 kg-m.) of energy, with an additional allowance in case the motor-generator set should, at some time, refuse to start immediately and the current remain on for several minutes before the set commenced to revolve. The steps of resistance are cut out by six short-circuiting switches, of the manually operated, multiple lever type, mounted on the switchboard.

AUTOMATIC SLIP REGULATOR

For the purpose of varying the slip of the motor-generator set, cast iron grid resistance is used, made up of three steps automatically switched in and out of circuit by slip regulators.

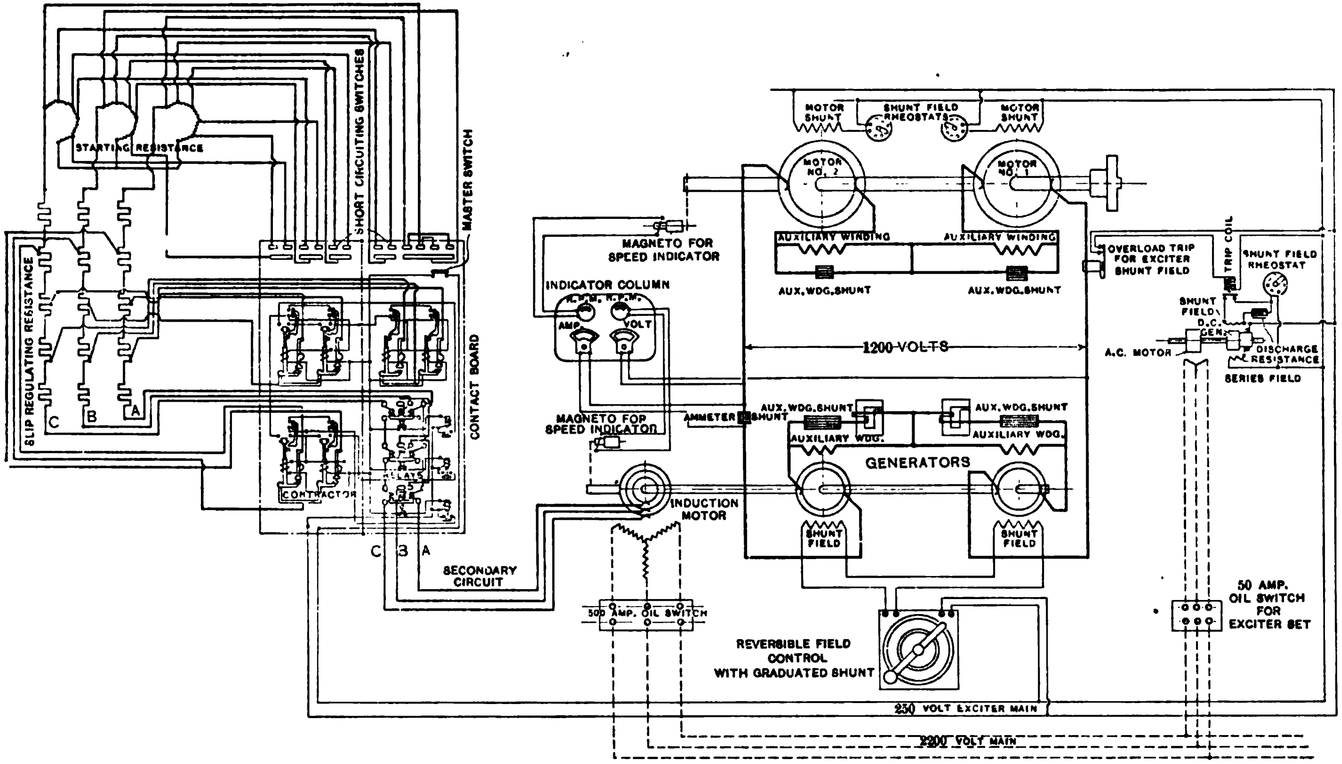


Fig. 8—Diagram of Connections for Rolling Mill Equipment

Each element of the slip regulator consists of a series relay and a contactor switch. The contactor switch is operated by direct-current solenoids on the 250-volt exciter main and is actuated by the opening and closing of the series relay. When the current in the rotor exceeds a certain fixed amount, the series relay breaks the current in the solenoid of the contactor switch, allowing it to open and insert resistance in the rotor circuit of the induction motor, thereby reducing the current and increasing the slip. These switches are interlocked in such a way that they will operate one after another in the proper order.

It was hoped that it would be possible to embody in this paper some figures showing the results of a test on the plant, but unfortunately the curve-drawing instruments to be used were not available early enough.

The equipment has been in operation, rolling steel, since December 10, 1911, and the results obtained indicate that the machines are well within the requirements, and that the mill motors are capable of being reversed with sufficient rapidity to meet easily any requirements in rolling. In a rough test made in order to determine the length of time required to reverse the motors, 22 reversals were made in one minute at 75 rev. per min., with the voltage on the 250-volt exciter mains reduced to 200 volts. The complete results of the test were not at hand in time for inclusion in the paper.

DISCUSSION ON "ELECTRIFICATION OF A REVERSING MILL OF THE ALGOMA STEEL COMPANY" (MCCORMICK), PITTSBURGH, PA., APRIL 26, 1912.

David Hall: The importance of apparatus of this kind and of the safety of operation so that there will be no breakdown is of such magnitude that each point has to be very carefully considered in the design, and there are a number of points regarding which I desire to ask some questions.

The successful operation of machines of such importance as these and of such magnitude is certainly a great credit to the engineers who are interested. I am to understand that the line circuit is grounded at the central point. The paper does not mention that, but I understand that is the condition of operation. I would like to be assured on that point.

B. T. McCormick: That is correct.

David Hall: I ask whether the shaft in the flywheel motor-generator set is one continuous shaft or whether there are certain couplings; if so, how many couplings are there? Of course, upon that point rests the possibility of dismantling a set for repairs, in case of an accident.

The arrangement of the generators in the flywheel set I notice is different from the arrangement of the motors, so far as the commutators are concerned. In the first case the commutators are adjacent to each other, and in the case of the motors the backs of the machines are placed towards each other. I ask whether there is a particular advantage in the arrangement of the generators in this manner. I also ask if either the motors or the generators are supplied with air from blowers.

The question of rapid reversal of the generators is, of course, of great importance, and I note that the reversal is given, I believe, as 22 reversals in one minute, if I am not mistaken. I ask if the motors reach full speed in such a reversal as that, or whether that is simply the motors reversing as fast as they can, coming up to a few revolutions, and reversing before they can reach full speed.

In regard to the excitation of the generators, I understand that is 250 volts excitation in the field; that is, the exciter is a 250-volt machine. In order to get rapid reversal I presume the actual voltage on the field of the generator is probably very much lower than 250, and I would ask what voltage that is, normally; what is the normal voltage across the field of the generator running at normal speed and normal voltage?

The surface speed of the commutator is mentioned as being very high, and the fact that it is mentioned naturally brings about the question as to what the speed is.

In regard to the reversing motor, some precaution is undoubtedly necessary to insure that the windings will not shift due to the reversal, and I ask in what manner the windings on the armature and commutator sets are braced to withstand the rapid reversals.

Wilfred Sykes: Mr. McCormick made the statement that the motor unit was divided into two machines so as to reduce the inertia. I have made investigations as to how much the inertia can be reduced by dividing it in two units, and find there is very little difference. The trouble, however, is that if you use a single machine it is necessary to go to very high voltage in order to reduce the current, or you run into difficulty with the commutators.

As far as the connection of the generators and motors is concerned, it has been my experience that it makes very little difference, when you have two generators and two motors, whether you connect in parallel or series, so far as the division of the load is concerned. I ask Mr. McCormick whether the output which is mentioned, 75 tons per hour, has been obtained over any period of time, such as a day, or something of that sort.

There is one point in connection with the control of the set that I will call attention to, and that is the overload trips. As far as I can make out, the only overload protection is a relay in the armature circuit which opens the field circuit of the exciter. I would like to know what protection is provided against sudden overloads which are liable to come with a cold ingot, or if the rolls are set down too far. It seems to me the overload trip is rather a roundabout way to protect the machines against overloads and make them immune to excessive fluctuations. For ordinary overloads this arrangement is all right, but I believe in addition thereto there should be an overload circuit-breaker provided in the main circuit which will open independently of this device which is mentioned.

There is another question I will ask Mr. McCormick, and that is in connection with the starter. Would it not have been preferable to have adopted a liquid controller, not only for the starting but also for the slip regulation, in the first place? That would have avoided the necessity of having magnetic switches and a water-cooled starter. I think the thing could have been very simply arranged so as to combine these two functions.

R. A. Black: The flywheel is stated here as being made in three sections of cast steel bolted together. I would like to know whether this is a better construction than the laminated construction, and if so, what are the advantages of having it this way?

Speaking of the rapid reversals ot the motor, I have had several cases of high-speed motors, and some very rapid reversing motors which gave a good deal of commutator trouble. I took the commutators and turned out grooves back of the brushes on either side, so that the brushes bore on just one surface, that is, there was no surface beyond the bearing of the brush, and I found by doing this that the commutator wear was reduced a great deal. In reversing the motor, there is always more or less tendency towards a little lateral motion, especially in high-speed reversing motors. High-speed motors running continuously which have in the past given a good deal of trouble are now running with very little sparking. This may be objectionable to some, but I find it much better. The brush ordinarily runs in one path, and by so doing, wears the commutator down somewhat, leaving a ridge on either side of the brush, so that when you get the end thrust, you have a little ridge which raises the brush, causing it to spark; this makes flat places, and the more it runs the worse it gets.

H. C. Specht: I ask the author of this paper how many foundation bolts are in the bedplate? In Fig. 7, it seems as if there are only four to six bolts in total. Further, I ask whether the bolts through the pedestals are used also as foundation bolts, or if they only tie the pedestals on the bedplate.

I will also make a few remarks in regard to the size of flywheels. In this particular outfit as described by Mr. McCormick it seems that the flywheel is rather large for the capacity of that mill. It is generally claimed that the load on the induction motor of the equalizing set is practically constant. This, however, is in many cases due to the very large flywheel and not due to the automatic speed control. As a matter of fact the automatic control acts too slowly to catch always the short peak loads. If the automatic control devices would actually catch the peak loads on time, the size of the flywheel could be reduced a great deal.

In many cases it may be recommended to connect into the secondary of the induction motor some permanent resistance, thus giving the automatic control more time to act, and the flywheel more chance to assist the motor immediately with the start of a peak load. Then, if desired, during the longer no-load periods, all the resistance may be cut out.

R. B. Treat: An equipment of similar nature was built for 250 volts, mainly because of the opinion of the Association of Steel Mill Engineers that 250 volts was about high enough. The large current was subdivided and delivered to several commutators in preference to one unduly large commutator.

Wilfred Sykes: I might say in connection with the voltage question that it is the usual practise in Europe to connect all the machines in series. I do not see the object of it where there are two generators and two motors. Where there is only one motor, or two motors, and there are two or three generators. then it is not possible to make the machine any other way, and the tendency in Europe has been to increase the size of the driving motors and concentrate as much power as possible on one machine, but, of course, in order to obtain generators capable of running at a reasonable speed, so as not to have the flywheels too large, smaller units have been used for the generators than for the motors. Some of the latest installations in Europe are using single motors in which the maximum capacity goes up to 15,000 h.p.

As to the question of inertia, it does not make much difference whether you put it in one or two units, at the present time. Four or five years ago the design of the machine was not as well understood as it is now; and then it did make an appreciable difference. In the first installation put in at Hildegradehuetts in 1906 there was a great advantage obtained by subdividing the motors, but with the present design it does not make much difference.

H. W. Cheney: I think I have little to say regarding Mr. McCormick's paper except to call attention to the fact that the starting resistance is quite unique and I should think could be comparatively small. The dimensions of the resistance are not given in the paper and I would inquire the approximate size of the resistance. It appears that the arrangement is such that a very large amount of energy should be dissipated with a very small element.

Bradley T. McCormick: Mr. Hall asked whether the shaft is made in one piece or in several pieces. The motor-generator set has one long shaft without any couplings.

He also asked why, on the motor-generator set, the commutators are facing each other, while on the mill motors the commutators face away from each other. In the case of the motor-generator set the two rotors are more accessible, for pressing onto or removing from the shaft, than they would have been if the commutators were turned the other way. On the mill motors I do not think it vital which way the commutators are turned, but probably from the standpoint of appearance the machines look better the way they are, with the armatures close together and the commutators on the outside. There are no blowers anywhere on the apparatus, neither on the generators, motors or induction motor.

The motors reach full speed on the reversals, and the test was made by throwing the controller handle back and forth as fast as it was possible to reverse the motors, the speed being read from the electrical speed counter. It was found that there was a lag in the response of the motors to the movement of the controller, so it was necessary to throw back the controller handle when the speed reached about 60 rev. per min. I made the test as above, and got eleven reversals in a half-minute, from 75 rev. per min. in one direction to 75 rev. per min. in the other direction, which corresponds to 22 reversals per minute.

A point was raised as to the voltage across the generator fields. Full voltage, of course, is not on the fields. A certain amount of it is dissipated in the rheostat, but just how much is on the field I should not care to answer. Concerning the commutator speed of the generators, I did not intend in my paper to give the impression that the commutator speed approached that of a turbo-generator. The commutator speed is 3500 feet per minute, which is no higher than commutators of motor-generator sets are usually run.

As to the matter of bracing the coils, I would rather not discuss that here, as it is an improvement of our own designing. We have gone very thoroughly into the question of bracing, and have secured the coils to the end heads or coil supports.

Mr. Sykes asked whether the full output of 75 tons an hour had been attained. Practically it has; I think, though, it is nearer 70 tons—70 tons seems to be about the run of the furnaces. There is no reason to think that 75 tons could not be obtained if it was desired to run the mill at that rate. Mr. Sykes also asked whether there is any additional overload feature. There is none, except the overload feature operated by the no-voltage relay on the exciter circuit. It will be, however, a very easy matter to put current trips on these, if it should be found necessary.

The question of a liquid controller has been brought up, and I see no reason why a liquid controller could not have been used to advantage on this system. It is of course a question of choice of a liquid controller vs. cast iron grid resistances, and this is largely a matter of personal taste.

Mr. Black asked whether it is better to have a flywheel cast in three sections of cast steel, than a laminated one. The flywheel in this installation does not revolve at such a speed that the strains set up in it are too great for cast steel to stand safely. The laminated steel flywheel is stronger, but of course much more expensive. By making the flywheel in three pieces, comparatively light steel castings are obtained, which are not apt to contain imperfections. They can be fitted together with reamed bolts, and for all practical purposes they constitute a solid flywheel. Mr. Black also suggested grooving the commutator in order to do away with difficulty due to end play, resulting in the wearing away of the brushes on the extreme inside ends of the studs. This matter we have taken up, not because we have had any such trouble, but I think the suggestion is a good one.

Mr. Specht asked how many foundation bolts we have. I do not remember, but will say that there are enough, and that the machines are well grouted in, so that the concrete comes almost level with the top of the base. The pedestal bolts form the top part of the foundation bolts. I agree with Mr. Specht that the flywheel is somewhat larger than necessary, but it was our intention to design this set along very liberal lines, and we intentionally made this flywheel large, to be on the safe side if the controlling apparatus should not quite fulfill our expectations.

There seems to be considerable discussion on the subject of voltage, and I am unable to understand why there should be so much criticism of 1200 volts when the neutral point is grounded. I suppose everyone realizes that if one should go over the system with a voltmeter he would be unable to find any point on the system where he could get a voltage to ground more than 600 volts; this is no more than would be obtained with a 600-volt parallel system with one side grounded, and the grounding of one side of a system, as everyone knows, often occurs without anyone finding it out until a ground occurs somewhere else on the system. However, with the middle point connected to the earth by a good heavy ground wire, if a ground does occur any where else in the system it will be burned off immediately.

The system which I have employed for the Algoma Steel Company has no more tendency towards overstraining the insulation by the working voltage, than the standard street railway generators which have been in use for so many years, where 600 volts or more is employed with the negative side grounded. Also, the liability of injury to operators by shock is no greater than met with in street railway practise.

Mr. Cheney asked as to the size of the water-cooled resistances. These resistance tanks are about three feet in diameter, and five feet high, and are quite liberal in water capacity. They hold enough water to start the motor-generator set several times, without replenishing the water.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 26, 1912.

THE OPERATION OF A LARGE ELECTRICALLY DRIVEN REVERSING ROLLING MILL

BY WILFRED SYKES

In a paper before this Institute[1] the author referred to the investigations that were made in Europe, preliminary to the installation of the first electrically driven reversing rolling mill, and it is interesting to note that somewhat similar experiments and investigations were made in this country, independently, with the same object in view.

About the middle of 1905, it was decided by the Illinois Steel Company to make inquiries regarding the possibility of installing an electrically driven reversing universal plate mill, and the engineers of that company made some preliminary experiments with a view to determining the power requirements and the probability of the success of such an installation. After sufficient data had been obtained, so that a power curve could be given to the manufacturers of electrical machinery, propositions were invited, and in the spring of 1906 a contract was let for the complete installation. The machines and apparatus were designed in June, 1906, and the complete equipment was delivered by the end of the year, and started in operation at the beginning of 1907.

In the meantime, the first European installation at Hildegradehuetts was started in operation and before the plant of the Illinois Steel Company was used commercially, a second European plant was started. It is interesting to note, however, that the installation of the Illinois Steel Co. was the second plant of this type to be ready for service. This plant has been in operation for approximately five years, and it is believed that a description of

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[1] *Electrically Driven Reversing Rolling Mills*, TRANSACTIONS A. I. E. E., 1911, Vol. XXX, II, page 1587.

some of the details of the installation and the results obtained, may be of interest.

The Illinois Steel Company was one of the earliest of the American steel works to utilize the blast furnace gases in gas engines, for supplying power for operating its mills, and the principal reason that led to the installation of this pioneer mill was the realization of the necessity for greater economy in the generation and distribution of power in such works.

The characteristics of the universal plate mill are such that it is necessary to have the greatest flexibility possible in the driving machine, and it was realized that by installing an electric motor, controlled by regulating the field of a special generator supplying it with power, an ideal system would be obtained, enabling all classes of work to be handled in the most desirable manner, the earlier passes being handled at low speeds and the finishing passes at high speeds, it being possible to obtain the maximum output of the mill on account of the flexibility of the speed control.

When the plant was installed, some doubt was felt as to the possibility of quick reversing, but in operation it was soon found that the electric plant was capable of handling material more quickly than similar steam-driven mills and more quickly than the material can be handled by the tables. After the plant had run for some time it was demonstrated that the electric equipment was not the weakest link in the chain. The following brief description of the mill and electrical apparatus will show, to some extent, the nature of the problem involved in the electrification and the methods adopted to insure successful operation.

MILL

The mill is of the two-high universal type, designed for rolling plates up to 30 in. (76 cm.) wide from slabs up to a maximum of 10 in. (25 cm.) thick. The main horizontal rolls are 24 in. (60 cm.) in diameter, and have a face of 34 in. (85 cm.). The vertical rolls, of which there are four, two on either side of the main rolls, are 14 in. (34.6 cm.) in diameter and have a face of 13 in. (32.8 cm.) The mill was designed to roll plates of all thicknesses and, on account of its flexibility, is used to a very great extent for handling small orders. The general layout of the mill is shown in Fig. 1, from which it will be seen that the motor-generator set, for supplying power to the main roll motors, is erected in the same room as the main roll motors. Apart from

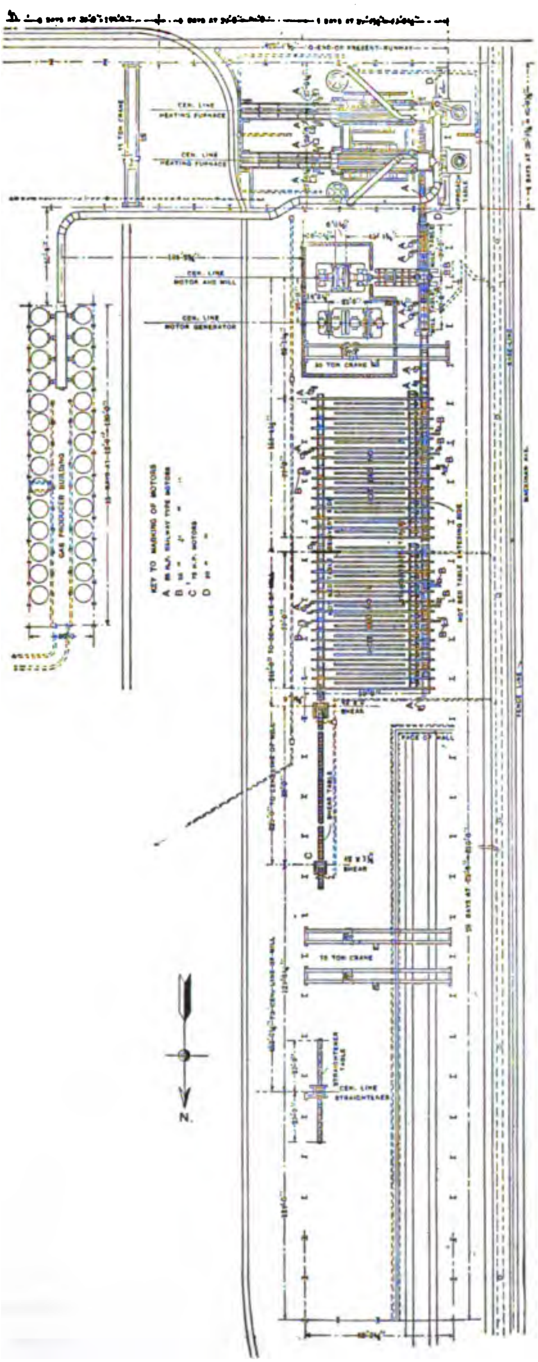


FIG. 1—GENERAL LAYOUT OF UNIVERSAL PLATE MILL AT THE ILLINOIS STEEL COMPANY'S PLANT.

the method of driving, the mill is not appreciably different from similar steam-driven installations.

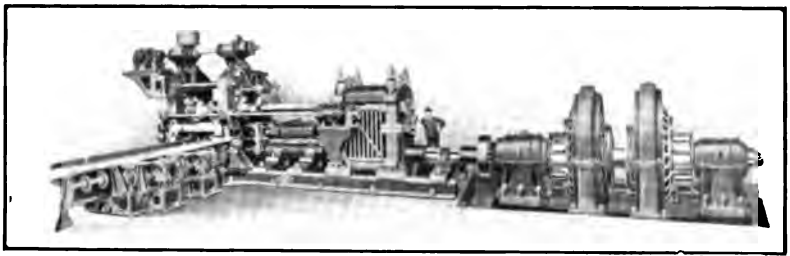
From the general layout drawing, it will be seen that the slabs are heated in two furnaces and carried by an approach table to the mill. When rolled, the plates are taken in two hot beds, and after cooling, to a shearing table, where they are cut to size and are then ready for straightening and shipment. The mill tables are operated by four 50-h.p. mill motors, the control being located at one side of the mill, close to the control for the main motors. The mill and the motor room are spanned by a 30-ton crane, which is capable of handling all parts of the equipment, with the exception of the flywheels of the motor-generator set.

In Fig. 2 a general view of the mill and motors is given, which shows the appearance of the complete equipment. The motors are enclosed in a separate room to protect them from the mill dust. In this view, the mill is shown complete with motor, but from Fig. 1 it will be seen that there is a wall between the pinion housings and the motors. In the illustration the auxiliary motors for the setting of the rolls are shown, that for the horizontal rolls being mounted to the left of the mill housings and that for the vertical rolls to the left of the pinion housings.

The setting of the horizontal rolls is varied by means of an electrically driven screw-down, the screws being operated by a 50-h.p. mill type motor. The setting of the vertical rolls is controlled by means of a 30-h.p. mill type motor, the position of the rolls being shown by the usual micrometer type of indicators. The main rolls are connected to the pinion housing by suitable spindles, arranged to allow a movement of about 12 in. (30 cm.). The lower pinion is driven from the roll motor through a coupling of the usual mill type, arranged to allow for considerable wear in the pinion shaft bearings. No flexibility is allowed for in the drive from the motor to pinions.

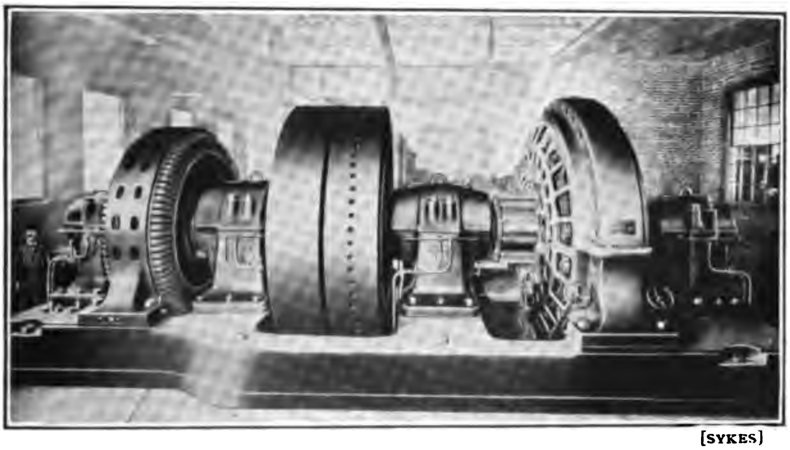
The mill was designed for a maximum speed of 150 rev. per min. but it has been found in practise that about 100 rev. per. min. is all that can be conveniently used, on account of the comparatively short plates rolled.

The capacity of the mill varies considerably on account of the material rolled, and depends more on the product required than on its capacity for rolling, and therefore definite figures cannot be given for the output for any particular product. In referring to some of the tests given, an idea of the capacity under various conditions may be obtained. The performance of a mill of this type



[SYKES]

FIG. 2—UNIVERSAL PLATE MILL AT THE ILLINOIS STEEL COMPANY'S PLANT, SHOWING THE MOTOR DRIVE



[SYKES]

FIG. 13—MOTOR-GENERATOR SET INSTALLED IN THE PLANT OF THE ILLINOIS STEEL COMPANY

PLATE XXVII
A. I. E. E.
VOL. XXXI, 1912

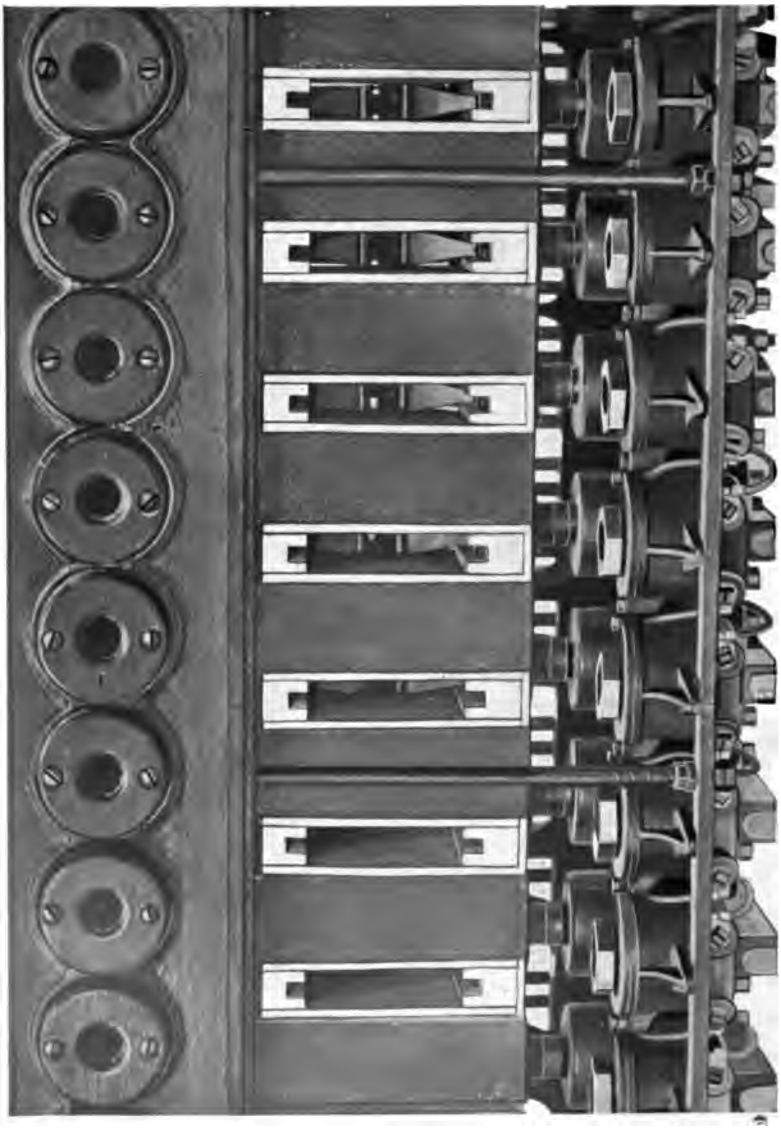


FIG. 15—VIEW OF SWITCHES USED FOR REGULATING SLIP

[SYKES]

cannot be compared with that of a blooming mill, rolling practically one size of material. The equipment of this mill had to be sufficiently large to handle the heaviest slabs that can be rolled, although the work is comparatively light most of the time and consequently the tonnage suffers.

SYSTEM OF DRIVING

In deciding upon the system to be used for driving the mill, and the control of the motors, the experience that had been gained in the design of large hoisting plants of the Ilgner type was drawn upon. In 1903 experiments had been made to determine the possibility of rapid reversing and the sensitiveness of this system of control, on a large hoisting plant. The results obtained indicated that, from the standpoint of control, this system gave all that could be desired, providing the proper provision was made to obtain a rapid change in the generator field. The ordinary solid-field generator cannot follow rapid change in the excitation on account of the eddy currents which are set up and which oppose any change of field strength. It is therefore necessary to design the machine with a completely laminated magnetic circuit so as to overcome this characteristic of the ordinary generator when working under the conditions met with in such service. The importance of having the voltage of the generator follow the changes of excitation quickly is very great from an operating standpoint, and this condition has been very well fulfilled in the Illinois Steel Company's installation.

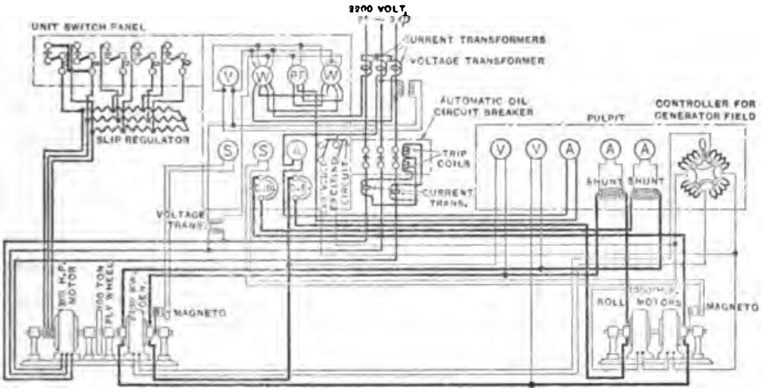


FIG. 3—DIAGRAM OF CONNECTIONS OF ELECTRICAL EQUIPMENT FOR UNIVERSAL REVERSING PLATE MILL OF ILLINOIS STEEL CO., SOUTH CHICAGO.

In Fig. 3 are shown the principal connections of this installation. It will be seen from this diagram that the roll motors are connected to a double-commutator generator without any starting resistance, each motor being connected to one commutator. This generator is driven by means of a three-phase induction motor, and a 100-ton flywheel is mounted on the same shaft. The roll motors are separately excited, the excitation being constant, with speeds up to 100 rev. per min., and the polarity is not changed. The direction of rotation and speed of the roll motors is controlled by changing the polarity of the generator, and varying its field strength, thereby varying the voltage applied to the armatures of the roll motors. This system avoids rheostatic losses, except in the field circuit, and enables any desired speed to be obtained, independent of the load.

The load on the generator naturally varies rapidly over a large range, the rate of change being at times 3000 to 4000 h.p. per second during acceleration and 8000 to 10,000 h.p. per second when braking. From the standpoint of the power supply, such a load would be highly undesirable, even for a very large power house, and could not be handled at all by gas-engine-driven stations of moderate capacity, such as usually found in steel mills. In order to equalize these fluctuations, the flywheel was provided to deliver energy during the periods of great demand and to store energy during periods of light load, and so that the flywheel may give up some of the energy stored in it, the speed must be reduced, and to store energy the speed must be increased.

To enable the flywheel to assist the three-phase motor in driving the generator, an automatic slip regulator was provided, which introduces resistance into the rotor when the current reaches a certain value, the speed being thereby reduced, and a portion of the energy stored in the flywheel is used for driving the generator. When the load on the generator is reduced, the resistance is automatically cut out, the speed consequently increasing, and energy is thereby stored in the flywheel. In practise, the maximum load on the line due to the reversing set is approximately one-fifth of the maximum load of the generator. By properly setting the regulator in relation to the work to be done, the input to the motor-generator can be maintained practically constant. It will be noted that the driving motor of the set is considerably smaller than the generator, which is due to the fact that the latter must be designed to carry the high peak loads, and as the heating of the armature is due principally to the copper loss, which varies as the square of the current, a much greater capacity is required to deliver a certain amount of power than would be necessary if the load were constant. The load on the induction motor does not vary greatly, and consequently it is designed to carry only the average load.

To protect the generator and driving motor against excessive overloads, due to "stickers" or cold slabs, overload trips for the circuit breakers are provided in each armature circuit, which are arranged to open the circuit at a load corresponding to approximately 8000 h.p. The primary circuit of the induction motor is provided with the usual instruments and overload protection. Speed meters showing the speed of the rolls, and double reading ammeters are provided on the operating pulpit, for the guidance of the operator. It has been found, however, that the electrical equipment is capable of performing heavier work than the mill, so that the operators are controlled during rolling more by the limitations of the mill than those of the electrical equipment.

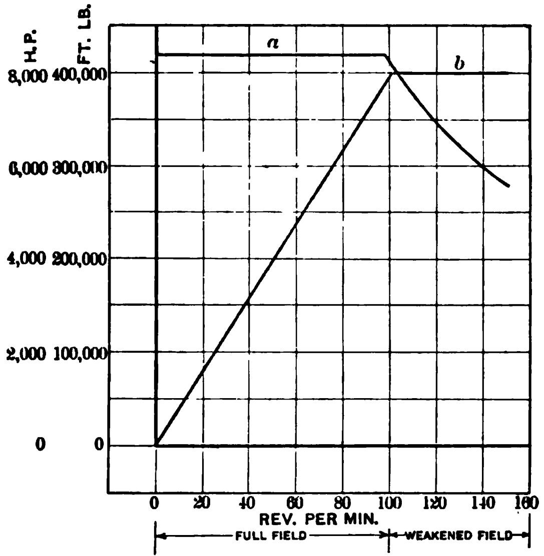


Fig. 4—Combined Rating of Roll Motors under Maximum Operating Conditions.

a.—Torque. b.—Horse power.

Driving Motors

The driving motors have a nominal rating of 2000 h.p. each, making a total of 4000 h.p. for the set. The maximum combined rating of the motors is shown in Fig. 4, which shows a maximum torque of 420,000 ft-lb. (58,086 kg-m.) at a speed up to 100 rev. per min., which is obtained with full voltage on the armatures. At speeds above this the horse power remains constant, the torque decreasing correspondingly, the higher speeds being obtained by weakening the field of the motors.

The motor was divided into two units, with the object of reducing the armature diameter, and consequently the inertia, and at the same time to facilitate handling the heavy current, which at 8000 h.p. is about 11,000 amperes. They are designed for a normal armature voltage of 575, and 220 volts excitation.

When the plant was designed, it was proposed to increase the speed from 100 rev. per min. to 150 rev. per min. for the longer passes, and, so as to insure that the flux in the motor fields would follow the quick changes of the exciting current, the magnetic circuit was laminated. Experience gained from the operation of the plant has shown that this refinement was unnecessary, although required in order to meet the original guarantees for acceleration and reversal asked for.

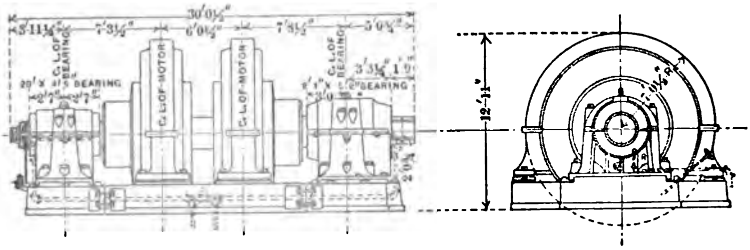


Fig. 5—Outline of Motors for Driving Mill.

The general dimensions of the machines are shown in Fig. 5, from which it will be seen that the two armatures are mounted on one shaft, supported by two bearings, the field frames being mounted side by side on the bedplate. The laminations are supported by a cast iron frame which is split horizontally to facilitate repairs. The machines are of the commutating pole, compensated type, the compensating windings being imbedded in the face of the main poles. The armatures, which are 7 ft. 6 in. (2.28 m.) in diameter, were especially constructed to stand the severe shocks anticipated with this class of work and to be capable of withstanding the severe stresses due to the rapid reversing and acceleration. On this account, very great attention was paid to the methods of supporting and holding the armature windings, a special steel ring being provided to support and fasten the end connections rigidly where they connect to the commutator lugs. With the ordinary construction, a certain amount of movement is always possible, and a very slight bending of the end connectors if repeated often enough will lead to crystallization and breaking, which has been demonstrated repeatedly where machines have been subjected to severe service. That the great care in supporting the end connections was justified, has been demonstrated by the fact that in some of the earlier European installations there was considerable trouble due to the breakage of the armature connections, whereas in the case of this plant there has never been the slightest difficulty from this cause.

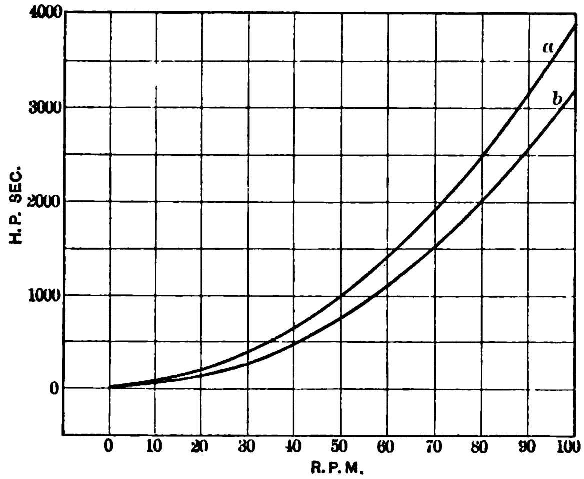


FIG. 6—CURVE SHOWING ENERGY STORED IN ROTATING PARTS OF ROLL MOTOR AND MILL.

a.—European installation. *b.*—Illinois Steel Company's installation.

The importance of reducing the armature diameter and weight will be appreciated on referring to Fig. 6, which shows the energy stored in the rotating parts of these motors at various speeds, the energy varying as the square of the speed. The inertia curve of a European installation is also shown, the rating of the two plants being almost identical. From these curves it will be seen that in the American installation the inertia has been kept somewhat lower than in the European plant, although the latter was installed about two years later.

Although very high efficiency in the motors of such an installation is not of very great importance, considering the other losses, yet it is desirable, inasmuch as it affects the heating of the machines, and a well designed machine will naturally have high efficiency. In Fig. 7 is shown the efficiency curve of these motors, from which it will be seen that the losses are extremely small. Of particular importance are the copper losses, which control to some extent the energy returned from the motors during braking, as the current is usually high and the period short. It will be noted that the bearing at the coupling end is unusually large, and at the maximum load the stress in the shaft is less than 3000 lb. (1360 kg.) per sq. in. (6.45 cm.).

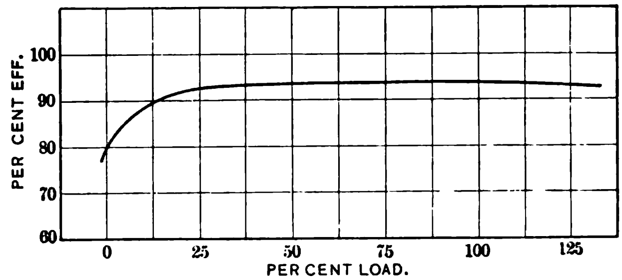


FIG. 7—EFFICIENCY CURVE OF ROLL MOTORS.
Two 2000-h.p. shunt motors—575 volts, 2800 amperes, 12-pole, 0-150 rev. per min.
Efficiency at 100 rev. per min., including excitation.

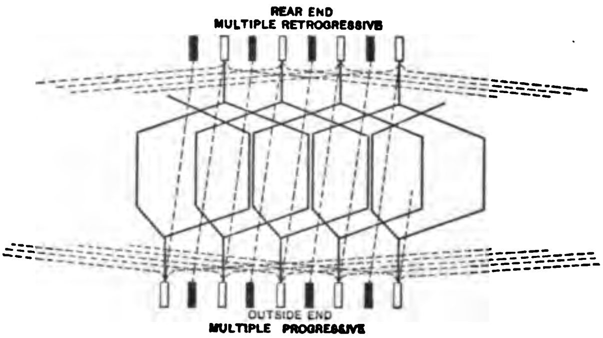


FIG. 8—ARMATURE CONNECTIONS OF DOUBLE-COMMUTATOR GENERATOR SUPPLYING POWER TO ROLL MOTORS.

The weight of the complete motor (two machines) is 356,000 lb. (161,488 kg.), made up as follows:

Rotating part	124,000 lb.	(56,245 kg.).
Fields	107,000 "	(48,534 ").
Base and bearings	125,000 "	(56,699 ").

MOTOR-GENERATOR SET

The generator of this set is of the double-commutator type, and embodies some design features of special interest.

It was decided to use a double-commutator type machine, so as to reduce the current to be collected from a single commutator, thereby allowing a single comparatively high-speed machine to be used. The field is of the laminated type, so built that it will answer changes of field current very rapidly, this being necessary to obtain quick reversing and speed changes.

The machine is of the commutating-pole compensated type, similar to the roll motors, the diameter of the armature being the same. The normal full speed of the generator is about 375 rev. per min. and the minimum speed about 300 rev. per min. At 375 rev. per min., the voltage of the generator with full field is approximately 600.

The armature winding is of especial interest, as there are twice as many commutator bars as there are coils, the equivalent of a half-turn coil being obtained by the connections, as illustrated in Fig. 8.

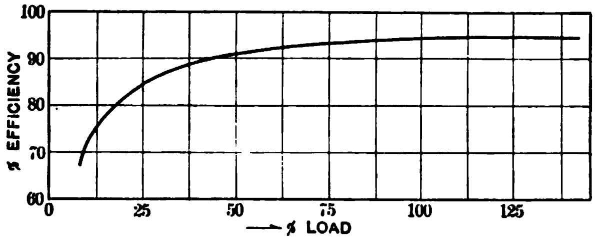


FIG. 9—EFFICIENCY CURVE OF GENERATOR SUPPLYING POWER TO ROLL MOTORS.

Shunt generator, 3000-kw. Efficiency at 300 rev. per min., including excitation.

The generator is designed for a normal capacity of approximately 3000 kw. and a maximum capacity of about 6400 kw. Special attention was given to the design of the generator, to insure good commutation under the severe conditions of operation. The commutating pole and compensating windings are not shunted, care being taken to render this unnecessary, so as to avoid any trouble due to difference in the self-induction of the windings and shunt affecting the division of the current with rapid changes of load. The necessity of commutating the maximum current with a weak field, requires that the closest attention be given to commutating characteristics of the generator.

The efficiency of the machine is shown in Fig. 9, this curve being based on tests made after the plant was installed.

The motor for driving the generator and flywheel has a normal rating of 1300 h.p., and is designed for three-phase, 25 cycles, 6600 volts, eight poles. It is of the wound rotor type, the rotor circuit being controlled by an automatic slip regulator, previously referred to, and is of the usual standard construction.

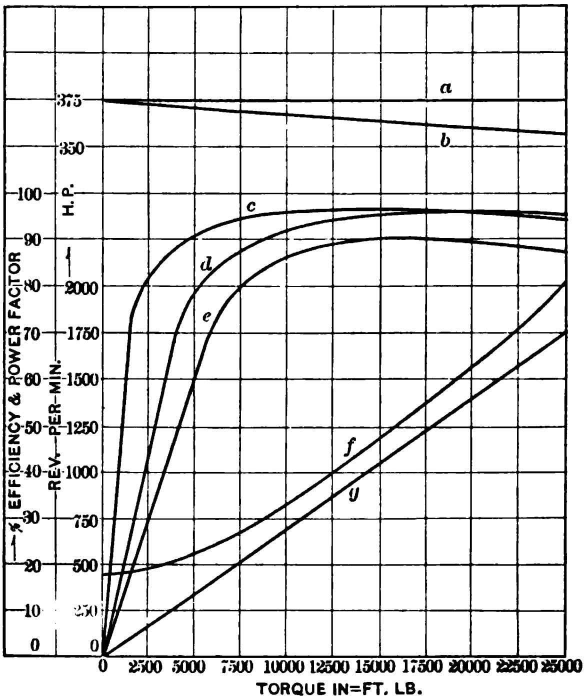


Fig. 10—Performance Curves of Three-Phase Motor Driving Flywheel Motor-Generator Set.

(1300 h.p., 2200 volts, 25 cycles, 8 poles, 375 rev. per min. synchronous speed.)
a—Synchronous speed. b—Motor speed. c—Real efficiency. d—Power factor. e—Apparent efficiency. f—Apparent h.p. g—Real h.p.

The performance of this motor is shown in Fig. 10, and the speed-torque characteristics for the various steps of the regulator are shown in Fig. 11.

The flywheel of this set presents some interesting features, as, owing to difficulties in transportation and in obtaining reliable steel castings, the wheel was built of comparatively thin punched laminations on a steel spider, the sheets being bolted between cast steel end rings. The peripheral speed of the wheel at 375 rev. per min. is 15,500 ft. (4724 m.) per minute. In order to facilitate handling, the wheel was built in two parts, each weighing 100,000 lb. (45,359 kg.), the total weight, therefore, being 100 tons. The flywheel effect of this wheel is 5,500,000 ft-lb., and under normal conditions of operation the speed of the set seldom falls below 320 rev. per min., and the input does not as a rule exceed about 900 kw. The energy stored in the wheel at full speed is 250,000 h.p-sec., and the amount given up when the wheel slows down to 300 rev. per min. is 90,000 h.p-sec.

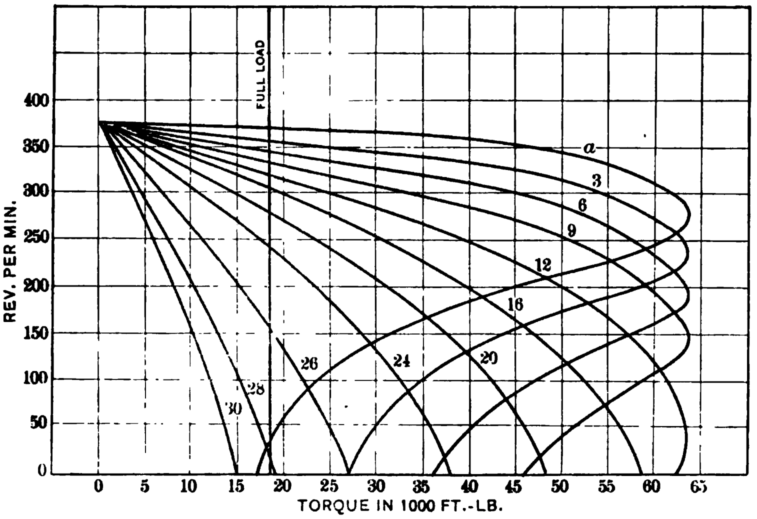


FIG. 11—SPEED-TORQUE CURVES OF THREE-PHASE MOTOR FOR DIFFERENT STEPS OF SLIP REGULATOR.

(1300 h.p., 2200 volts, 25 cycles, 8 poles, 375 rev. per min. synchronous speed.)
Curve *a*—Rotor ring short-circuited. Curves *a*-3-24—Running. Curves 24-30—Starting.

The general assembly of this set is shown in Fig. 12, which gives the principal dimensions, and a view of the complete machine is shown in Fig. 13. The rotating parts are supported by four bearings, the flywheel having a bearing on either side and a separate shaft. The shafts for the motor and generator are supported at one end by a bearing, and at the other are bolted to the flywheel shaft. The maximum bearing pressure has been limited to approximately 80 lb. (36 kg.) per square in. (6.45 sq. cm.). Both machines and the flywheel are mounted upon a single base plate, which is securely fastened to the foundation by numerous bolts. All bearings are water-cooled and oiled from a central gravity oil system, so as to insure a continuous supply of oil to all wearing parts. In order to facilitate starting the set, a pneumatic barring gear is provided, controlled by a hand-operated triple valve.

Control Apparatus

For controlling the excitation of the generator, a special controller, operated on the principle of a Wheatstone bridge, was designed, the connections of this controller being shown in Fig. 3. The current handled by this controller is, approximately, 50 amperes, with maximum excitation, which can be readily handled by a controller of the face plate type. The slip regulator for automatically varying the rotor resistance, so as to limit the input, consists of a number of pneumatically operated switches, arranged in groups, their operation being controlled by two relays. One of these relays causes the switches to drop out when the current in the primary of the motor reaches a certain value, and so long as this relay is open the switches will continue to drop out successively. When the current reaches a normal value, the relay closes and no further switches are opened. When the current falls below the normal, the second relay drops, and causes the switches to close automatically in the proper order, and in this way the input to the motor, under normal operating conditions, is maintained approximately constant.

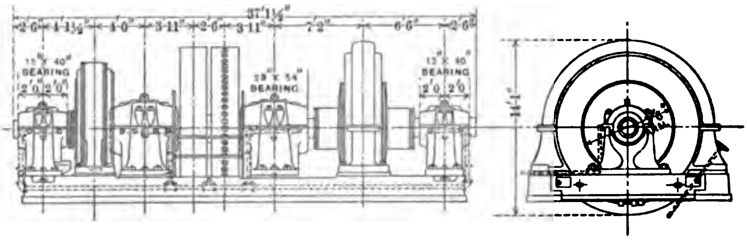


FIG. 12—OUTLINE OF FLYWHEEL MOTOR-GENERATOR SET SUPPLYING POWER TO ROLL MOTORS.

The connections of this regulator are shown in Fig. 14, and in Fig. 15 is shown a group of the pneumatic switches, which are of the same type as used for the control of large electric cars and locomotives. In all, thirty switches were provided for starting and regulating the speed of the motor, and, consequently, the resistance is varied in very small steps. The capacity of these switches to withstand very severe service has enabled them to be operated successfully since the plant was installed, although each switch may be closed or opened eight or ten times a minute.

Test Results

After five years' operation of the plant, it was decided that it would be advisable to make a complete set of tests, to dedetermine, not only its operating characteristics, but also whether such an installation could be improved upon and how closely the designed capacity approximated to the actual operating conditions. Owing to the difficulty in obtaining suitable apparatus to make such tests, most of the instruments were specially designed and built for this test. The current in the motors varies, under normal conditions, so rapidly that ordinary indicating or recording instruments were not suitable and it was therefore decided to use an oscillograph for recording the direct-current voltage and current. The speed of the roll motors was recorded by means of a special graphic recording

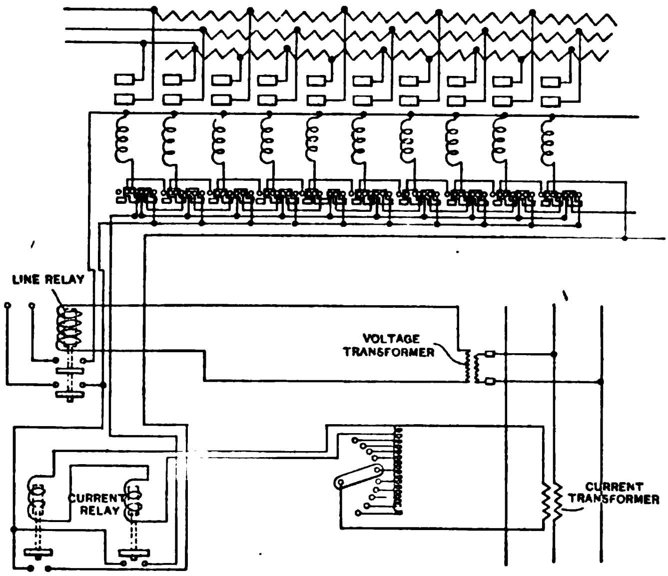


Fig. 14—Diagram of Connections of Automatic Slip Regulator Controlling Input to Flywheel Motor-Generator Set.

meter, controlled by a suitable magneto, driven from the motor shaft. The recording instrument was especially designed so as to be capable of following rapid changes in speed, and to avoid errors usual with graphic instruments. It was decided to avoid the use of a pen for recording and the position of the pointer was recorded by causing a spark to pass from the end of the pointer through the paper to an insulated plate. In designing these instruments, provision was made to avoid introducing errors in the readings due to the static effect of the high-tension current for the spark. The speed-recording instrument for the roll motors had a center zero so as to record both directions of rotation.

The speed of the motor-generator set was also recorded, to determine the amount of energy given up or absorbed by the flywheel, during the period of test. The instrument used was similar to that adopted for the recording of the motor speed, except that provision was not made for recording the speed in both directions. In order to obtain a large reading for a comparatively small change of speed, a battery was connected to oppose the magneto, and the meter recorded the difference in the potential of the magneto and the battery. All the instruments, including the oscillograph and the speed meters, were provided with a time-recording device, all of these attachments being controlled by a single contact-making clock.

The input of the motor-generator set was determined by means of a wattmeter of the same type as the speed meters.

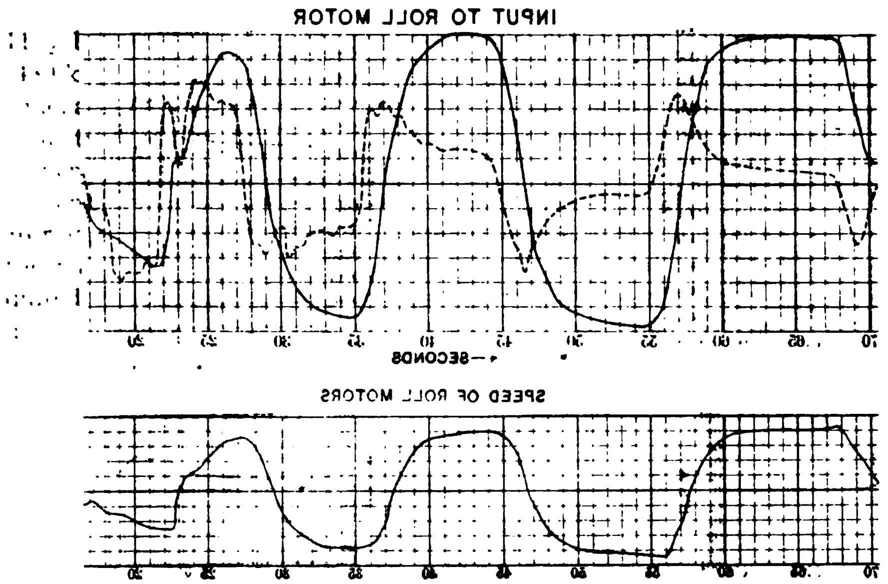
In addition to the above apparatus, provision was made for recording signals from the mill. In the mill, records were obtained as to the size and weight of material rolled and the reduction per pass, and at the same time readings were taken to determine the temperature of the metal.

These tests gave, simultaneously, readings of the input to the roll motors and the input to the motor-generator set at the speed of the set and motors.

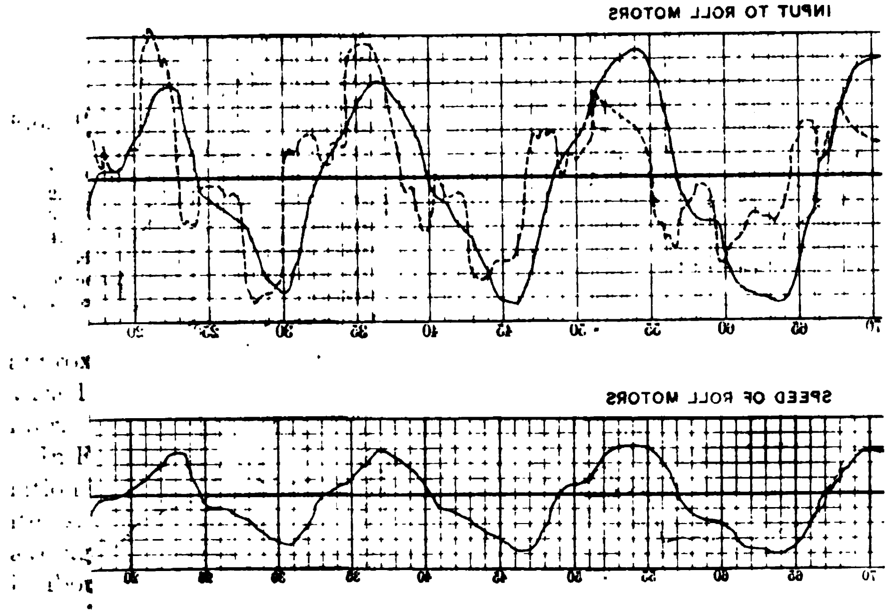
With this information, together with the known characteristics of the apparatus, and the data obtained as to the work done by the mill, it was possible to obtain a complete analysis of the power requirements and operating characteristics.

While it is not possible within the scope of this paper to go into detail as to these tests, a few characteristic curves are given which may be of interest.

Fig. 16 shows the power required for rolling a slab, 3½ by



…URVES SHOWING INPUT TO ROLL MOTORS AND SPEED WHEN ROLLING SLA…
TO PLATE 3/16 BY 12 IN.
(See details given under Fig. 17.)



…ORS AND SPEED WHEN ROLLING SLAB 3 BY 30¼ BY 75.9 IN. TO PLATE ¼ BY…
(See details given under Fig. 19.)

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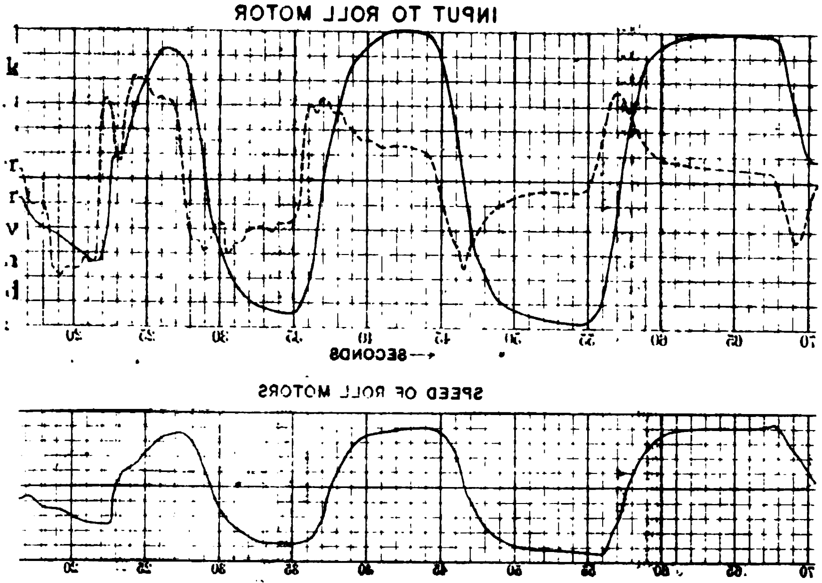
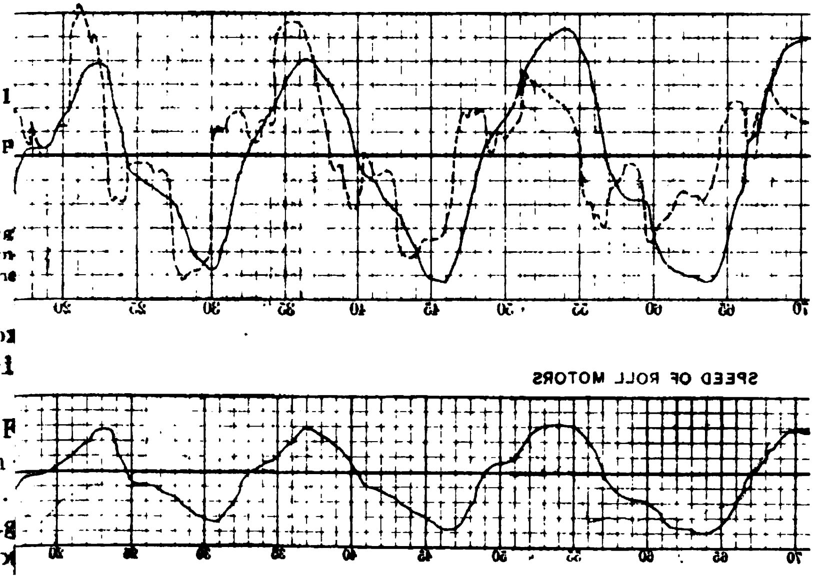


URVES SHOWING INPUT TO ROLL MOTORS AND SPEED WHEN ROLLING SLA
TO PLATE 5/16 BY 12 IN.
(See details given under Fig. 17.)



ORS AND SPEED WHEN ROLLING SLAB 3 BY 30½ BY 75.9 IN. TO PLATE ¼ BY
(See details given under Fig. 19.)

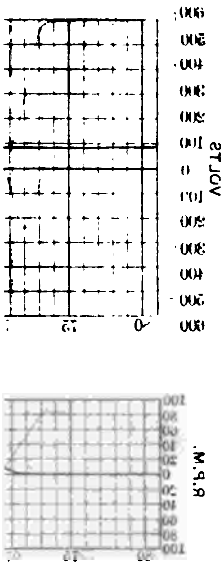


Fig. 16—Test C

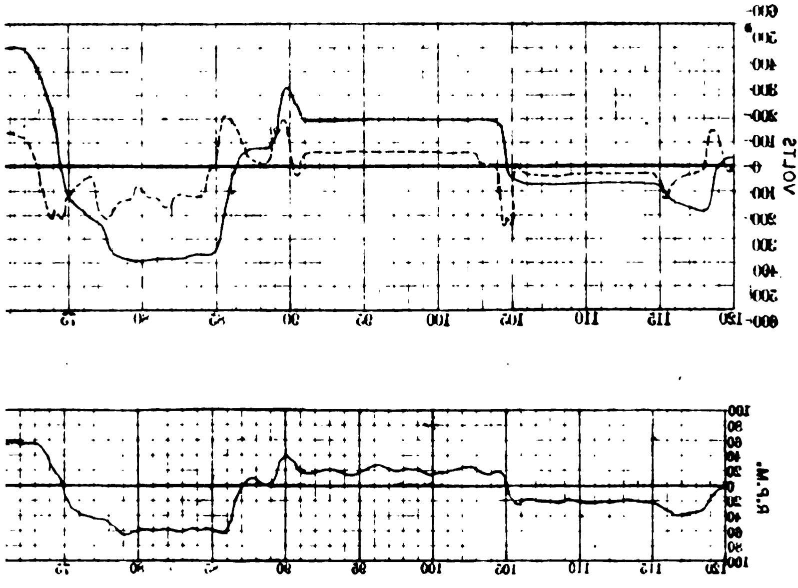


Fig. 18—Test Curves Showing Input to Roll Mot

11½ by 95 in. (8.9 by 29.2 by 241 cm.), weighing 1080 lb. (489 kg.), to a plate $\frac{5}{16}$ in. (7.9 mm.) thick by 12 in. (30.5 cm.) wide, and 1060 in. (26.9 m.) long. From these curves it will be seen that the maximum current was approximately 4100 amperes, and the maximum braking current about 2350 amperes. The maximum speed of the rolls during this test was 86 rev. per min. during the sixth pass, whereas in the first pass the maximum speed was 50 rev. per min. The total time required from beginning to end of the test was 58 seconds, showing a maximum capacity when rolling this size material of approximately 30 tons per hour. The temperature of the metal varied during the test from 1920 deg. fahr. to 1800 deg. fahr.

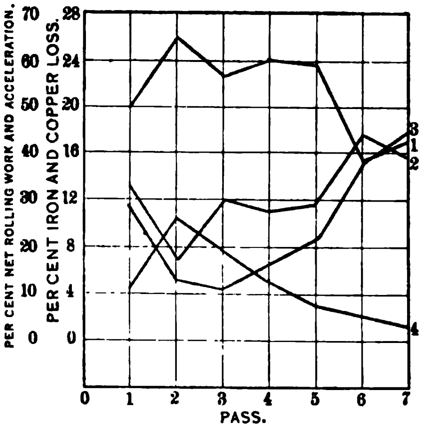


FIG. 17—ANALYSIS OF POWER INPUT TO ROLL MOTORS WHEN ROLLING PLATE (SEE FIG. 16).

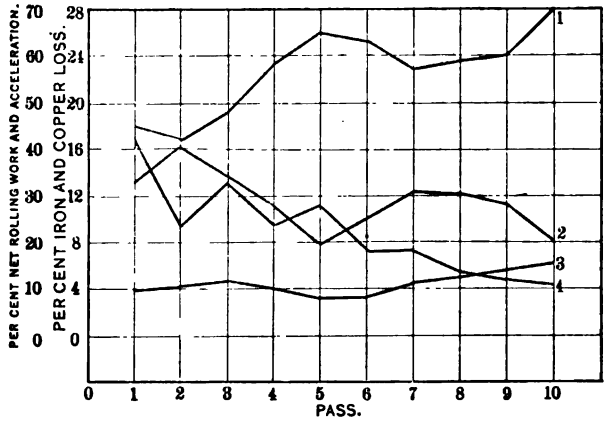
1. Percentage of net rolling work to total input.
2. " " acceleration " " " "
3. " " friction & iron loss " " "
4. " " copper losses " " "

Original slab 3½ by 11½ by 94.9 in. Finished plate $\frac{5}{16}$ by 12 by 1016 in.—Temperature of metal 1860 to 1810 deg. fahr.—Composition: Carbon 0.10 %, Phosphor 0.033 %, Manganese 0.51 %, Sulfur 0.044 %.—Ultimate tensile strength 53,000 lb. per sq. in.

In Fig. 17 is shown an analysis of this test, which gives the relation between the total input to the roll motors and the various items. It will be seen that the percentage of net rolling work averages about 55 per cent. The input required for acceleration is about an average of 30 per cent. The loss due to friction of the mill and iron loss in the motors is approximately 10 per cent. The average copper loss is about 5 per cent.

The reason for the very large drop in the percentage of net roll work in the last two passes, is the fact that the draft was comparatively light on these two passes.

The comparatively large proportion of the input required for acceleration shows the importance of keeping the inertia as low as possible, and the great advantage of the voltage control system is that it enables a considerable proportion of this energy to be recovered. In this particular test, the total energy required to accelerate the motors for the seven passes was 11,800 h.p-sec. and there was returned by the motors to the generator 8317 h.p-sec. or somewhat more than seventy per cent. It should be noted that with this system the energy taken from the generator is only half what it would be if rheostatic control were used and that with the latter system none of the energy would be recovered. In this test, if rheostatic control had been used, the total energy required for acceleration would have been 23,600 h.p-sec., which would have increased the total net input to the motor about 50 per cent.



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1. Percentage of net rolling work to total input.
2. " " acceleration " " " "
3. " " friction & iron loss " " "
4. " " copper losses " " "

Original slab 3 by 30¼ by 75.9 in. Finished plate ⅜ by 30 by 612 in. Temperature of metal 2030 to 1200 deg. fahr.—Composition: Carbon 0.18 %, Phosphor 0.025 %, Manganese 0.48 %, Sulfur 0.038 %.—Ultimate tensile strength 62,900 lb. per sq. in.

In Fig. 18 are shown the curves when rolling a slab 3 by 30 by 76 in. (7.6 by 76 by 193 cm.) weighing 1960 lb. (889 kg.), to a plate

⅜ in. (9.5 mm.) thick by 30 in. (76 cm.) wide. The total time of the test was 100 seconds, indicating a maximum capacity of the mill when rolling these slabs of approximately 36 tons per hour.

It will be seen from these curves that the maximum loads are considerably higher than shown in Fig. 16. In this case, the maximum current input is slightly in excess of 6000 amperes, and the braking current reaches a maximum of, approximately, 3150 amperes. The maximum speed of the mill did not exceed 75 rev. per min. during any pass. The temperature of the metal during this test varied from approximately 2040 deg. fahr. to 1300 deg. fahr.

In Fig. 19 is shown an analysis of this test, from which it will be seen that the percentage of net rolling work to the total input gradually increased, and the percentage of power required for acceleration decreased. The copper losses decrease on account of the maximum current being smaller, and naturally the friction loss increases as the mill is running the greater percentage of the time.

The percentage of energy returned by the roll motors was about 62 per cent of the input for acceleration. An examination of a number of other tests taken at random gives the following figures:

	Input for acceleration	Energy returned during braking	Percentage
1	21,610	14,197	66
2	21,700	14,215	65.5
3	18,855	10,657	56 5
4	18,208	12,512	68.7
5	17,035	9,105	53.5
6	20,320	12,449	61.5
7	23,800	15,546	65.5
8	18,620	12,111	65
9	29,195	24,058	82.2
Total	189,343	124,850	66

The power required to displace the metal varies considerably, depending upon the operating conditions. The absolute figures depend upon the temperature of the metal, its composition, and the type of mill, etc.

Fig. 20 shows a characteristic curve, when rolling plates on this mill, from which it will be seen that the power required increases very rapidly with the reduction in thickness, this being due to the greater density of the metal, the lower temperature, and the lower rate of displacement.

The total power required for rolling varies considerably, and no definite rule or formula can be produced that will cover all the conditions. The relation of the amount of metal displaced during the earlier passes, to the total, and such items as the temperature, amount of draft, number of passes, etc., make it impossible to give general figures. The net rolling work which is independent of the losses in the equipment also varies widely, and a thorough knowledge of the conditions is necessary to predict the power requirement of an installation. In Fig. 21 are shown some curves of the net rolling work per ton plotted against elongation and it will be seen that the variation is considerable. The difference in the total power required may show a much greater variation than given, but these curves will indicate in a general way how the net rolling work varies with the displacement of the metal. In a test made when rolling a certain slab, in seven and in fifteen passes, the net rolling work showed a difference of about 10 per cent, but the total input varied about

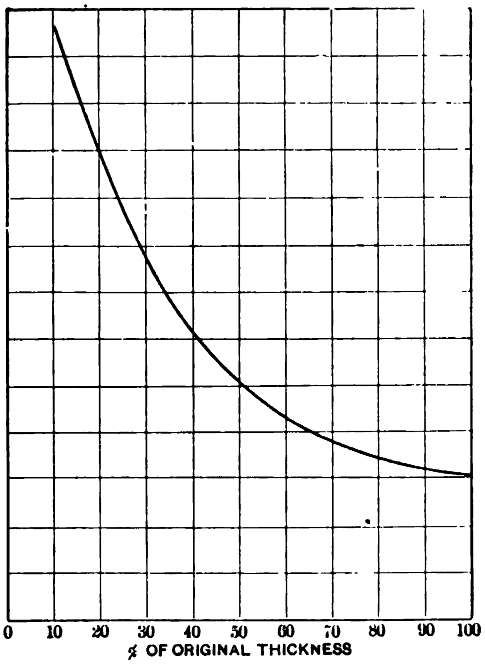

FIG. 20—CURVE SHOWING INCREASE IN POWER REQUIRED FOR DISPLACING METAL WITH REDUCTION IN AREA.

50 per cent, due to the reduced capacity of the mill when rolling at the lower rate. Such points as these show the importance of a very close examination of operating conditions when designing a mill of this kind, and to insure success an electrically driven reversing rolling mill requires very careful engineering, as the problem is not so much to get a mill that will work, as to get one that will work economically.

At times great stress has been laid upon the advantage and necessity of very rapid acceleration and reversal. The author has pointed out previously that this feature is of little importance, as, with a well designed plant, the roll motors can be handled more quickly than the material to be rolled. In this mill it is the general practise during the earlier passes to have the feed rolls running at full speed in the opposite direction to main rolls, so that when the slab leaves the mill, it is returned in the shortest possible time. In spite of this, the main motors are easily capable of reversing in ample time. An examination of a large number of tests on this and other mills shows that the average rate of acceleration used does not exceed about 20 rev. per min. of the rolls per second, the maximum being about 30 rev. per min. per second. The rate of retardation is, however, very much greater and generally varies between 40 and 50 rev. per min. per second.

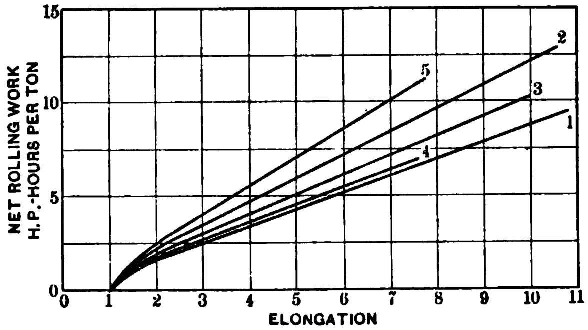

FIG. 21—TYPICAL TESTS SHOWING POWER REQUIRED TO ROLL PLATES FROM SLABS.

	Slab		Plate		Temperature, deg. fahr.
1.—4 by 21.5 by	95 in.	to ⅜ by	21¼ in.;	2160 to	1536
2.—4 " 21.5 "	60 "	" ⅜ "	21⅛ "	2172 "	1578
3.—4 " 8 "	100 "	" ⅜ "	8⅜ "	2208 "	1944
4.—6 " 9½ "	90 "	" ½ "	10 "	2076 "	1800
5.—6 " 7¾ "	82 "	" ½ "	8 "	2016 "	1692

The over-all efficiency of the plant depends in the first place

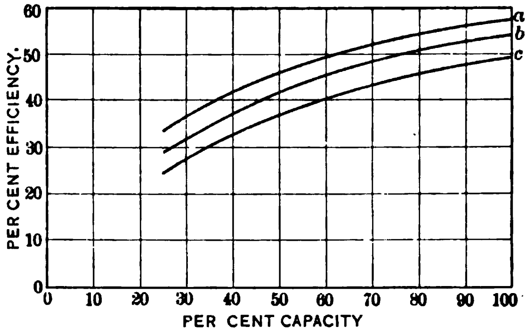

FIG. 22—OPERATION OF UNIVERSAL REVERSING PLATE MILL UNDER VARIOUS CONDITIONS.

Over-all efficiency, from input to power required to displace metal, including mill friction.

a. Rolling slab 7 by 30½ by 76 in. to ⅜ in. plate.
b. " " 5 " " " " " " " " "
c. " " 3 " " " " " " " " "

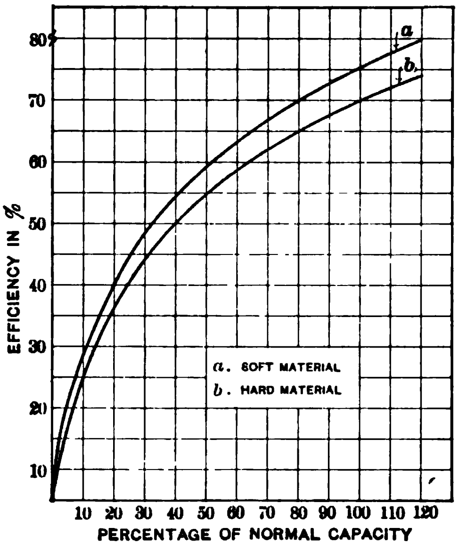

FIG. 23—CURVES SHOWING THE OVER-ALL EFFICIENCY OF ELECTRICAL EQUIPMENT AND MILL WHEN ROLLING INGOTS TO BILLETS.

upon the relation of the size of equipment to the material to be rolled. As already pointed out, a mill of this kind cannot be compared to one rolling only a single product, in which case the operating characteristics can be very accurately predicted. As this mill will be often underloaded, the efficiency naturally suffers, which is true, independent of the system of driving. In Fig. 22 are shown some over-all efficiencies when rolling slabs of various sizes, and it shows how the results improve with an increasing load. In addition to the losses in the electrical equipment, these curves also allow for the friction of the mill. To show the difference that the underloading, when rolling the smaller slabs, makes upon the efficiency, compared to what can be obtained when the mill is designed for one class of product only, there are presented in Fig. 23 the over-all efficiency curves of a blooming mill taken from a previous paper by the author.[2]

The results obtained from this mill indicate that although the equipment was built six years ago, it compares very favorably with some of the latest designs and is quite capable of meeting the most severe service it may be called upon to perform. In new designs, certain features would be improved upon, with the object of somewhat simplifying the equipment from a manufacturing standpoint, but it is not believed that any great improvement could be made from an operating standpoint, as since it has been in regular service the electrical equipment has given no trouble. The experience gained has shown that the engineers of the Illinois Steel Co. were thoroughly justified in undertaking this pioneer installation without having any precedent whatever to work upon.

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[2] *Electrically Driven Reversing Rolling Mills*, TRANSACTIONS A.I.E.E., 1911, XXX, II, page 1599.

DISCUSSION ON "THE OPERATION OF A LARGE ELECTRICALLY DRIVEN REVERSING ROLLING MILL" (SYKES). PITTSBURGH, PA., APRIL 26, 1912.

R. A. Black: The discussion has been on electrically operated rolling mills. A question comes to my mind as to the comparative cost of electrically operated versus steam-operated mills. This is one thing that electrical engineers are facing now, the question of which pays. I heard the superintendent of a large steel mill say recently that this subject has never been taken up and thoroughly discussed, and that he had never been able to find any comparison of the cost of operating an electrical mill and a steam-driven mill. Is it better? Is it cheaper? Does it pay to operate electrically? Which is the more flexible? Can you turn out steel as quickly and as economically with electric as with steam-operated mills?

As I understand the construction of the electrically operated reversing mills, there is a motor-generator set with a heavy flywheel between the switchboard and the mill motor which takes all undue stress from the switchboard, this being accomplished by the energy stored in the flywheel. Is there any particular kind of steel mill service that steam is better adapted to than electric drive? For instance in bar, billet, slab, or plate mills, would steam be better on some and electricity for others?

H. C. Specht: I wish to ask the question in which case it is right to use a reversing mill and in which case a three-high mill. The difficulty of the three-high mill is well known among steel men. As we have a number of steel engineers in this meeting, it would probably be very interesting to hear how serious the difficulties of the three-high mill are and if there is really in all cases enough reason to use the two-high reversing mill, instead of the three-high mill. From the electrical point of view, the three-high mill would work more economically than the two-high reversing mill. The over-all working efficiency of large motors on a three-high mill is generally at least 86 per cent, whereas with a two-high reversing mill it probably would not exceed 64 per cent.

R. Tschentscher: The questions which Mr. Specht has asked in connection with the relative economy of the three-high versus the two-high mill, were discussed by me at quite considerable length at the Chicago meeting of the American Institute of Electrical Engineers, in connection with Mr. Sykes's paper, and I think covered about all I have to say on the subject. There is quite a difference of opinion on the subject. Mr. Specht mentioned 86 per cent on the three-high mill versus 64 per cent on the two-high mill. I think that can be immediately dismissed after it is stated. There are so many factors which enter into the proposition, that efficiency is really a term which can only be mentioned in connection with the full-load operation. There are many other questions of mill practise that enter into the rolling, which are of much more vital importance than the mere statement of the relative efficiency of the electrical equipment. One equipment with a full load efficiency of 60 per cent may be a more economical outfit than an equipment having a full load efficiency of, perhaps, 90 per cent.

All these problems, from my point of view, are local problems. The question of steam operation versus electrical operation is a local problem. If the cost of fuel, the cost of getting power, is low, at the mill—I am speaking now of steam power—it is possible that a steam-driven mill may be the more economical to put in. If the local mill is at some distance from what is considered a waste product in the steel plant, for instance, blast furnace gas, there seems to be no question but that electrical drive is the more economical. The questions of up-keep, the questions of steel supply, the questions of the output of the particular plant involved, all must be taken into consideration.

Mr. Specht asked the question as to whether the electrical reversing mill was better adapted for one class of output than another. I went into that subject quite carefully to the extent of obtaining the opinion of men who are considered high-grade rolling mill men, and I believe that the consensus of opinion is that a three-high mill will give a larger total output for billets than a two-high mill, but for plates a two-high mill will produce a larger output, and in many cases a better quality of output.

The question of quality is now of as much, if not more, importance, than the question of output. If we can obtain better quality by the use of the two-high mill, with its graduated speed control, that is a factor which is going to appeal to rolling mill managers much more than it has in the past. We do not hear so much of the word " tonnage " now as we did six or seven years ago. The question of safety brings in the point of voltage and the question of quality.

James Farrington: I ask Mr. Tschentscher to express his opinion of the two-high mill, relative to the three-high mill, as to the cost of upkeep, if he has that information.

R. Tschentscher: There have not been enough data available from a three-high mill, electrically driven, versus the two-high mill, electrically driven, from the standpoint of the upkeep of the mill equipment, to give anything definite; but a comparison between two-high and three-high mills, steam-driven, leaves no question as to the relative cost of up-keep. I think one of the biggest points in the three-high versus the two-high electrically driven mill is the fact that the two-high mill can be shut down instantly, and that there will be a great many more minor repairs made in the case of the two-high mill than in the case of the three-high mill. In the three-high mill shutting down or starting up involves considerable delay, and those small troubles which may come up, which are corrected in the two-high mill, are left in the three-high mill until they assume considerable magnitude, before they are given attention, resulting in more expense and greater delay.

E. Friedlaender: With regard to reversing mills and straight-running mills with flywheels I would like to make a few remarks. The reversing mill is much more extensively used in Europe than in this country, due to the fact that rolls can be arranged for a number of different sections and in Europe they seldom run on straight work for any great length of time, sometimes changing rolls two or three times a day. For this reason the reversing mill is much handier for them, saving thousands of dollars on rolls by not using the straight-running mill for different products. When a mill is designed for certain products and runs most of the time on the same product, a three-high mill is preferable, therefore I think the reversing-mill will continue in the future to be more in vogue in Europe; and, as has been shown in recent installations, a compound condensing steam engine with flywheel direct-connected to the roll is going to be hard to compete with, as regards cost, when compared with electric generators at the power house, transmitting the power, say, one-half or one-quarter of a mile, at high tension, and going through motor-generator or direct to the motor, unless the power is generated at a very low cost without the use of steam. In the Pittsburgh district we have generated power at a very low cost, and have found out that in considering only the operation and repair of the motor, electrically driven mills are more cheaply operated, but when considering the repairs to the total installation, it is found that the modern compound condensing steam engine supplied with a flywheel is very hard to beat.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 27, 1912.

ELECTRICAL CONTROL OF A LARGE MINE HOIST

BY H. W. CHENEY

The most serious problem encountered in the application of electric drive to large mine hoists is that of electrical control. It is necessary, in order to secure continued successful operation of an electric hoist, to furnish a control system which is absolutely reliable at all times. The design must be such that all parts of the apparatus will withstand the most severe, and even unreasonable, conditions of service without giving trouble and without repeated attention and repairs. It should be so designed that it is impossible for the operator to damage the controller or any part of the machinery by a wrong movement of the operating handle or by misjudgment of conditions.

This may be said of electrical control in general, but it applies with particular force to mine hoists, which are usually located remote from supply centers, are operated by men who are unfamiliar, as a general rule, with electricity, and where delays in operation mean tremendous losses to the mining companies.

In the electrical control of large induction motor-driven hoists, of which there are, to date, very few in this country, conditions are unusually exacting. The embodiment of all the desirable features of control for this class of service is a problem of no small moment, and is deserving of the best efforts and attention of engineering talent, for the advantages of the use of large induction motor-driven mine hoists are many and their use will become more general with the advent of suitable means of control.

It is the purpose of this paper to give a description of the general layout of a mine, an electrically driven mine hoist, a more complete description of a novel control system embodying a liquid rheostat employed for the the control of the hoist motor, and to outline some of the tests made upon the entire outfit during actual operation.

An electrical mine hoist (see Figs. 1 and 2) was installed at the No. 3 iron mine of the Woodward Iron Company at Woodward, near Birmingham, Ala., and was ready for operation in December, 1909. It is of the unbalanced type, and consists of a single drum 8 ft. (2.4 m.) in diameter and 40 in. (1.01 m.)long, with winding space for 2500 ft. (762 m.) of 1½-in. (3.8 cm.) wire rope. The drum is provided with a band brake which is automatically applied by a weight and released by air pressure under the control of the operator. It is driven by a 500-h.p., three-phase, 25-cycle, 375-rev. per min. wound-rotor induction motor through a flexible coupling, triple reduction gear and an air-operated friction clutch of the Lane type. The hoist is designed for a maximum rope speed of 750 ft. (228.6 in.) per minute, and a maximum rope pull of 25,000 lb. (11,339 kg.)

Provision is also made for hand operation of the clutch and band brake from the operator's platform, to provide means for operation in case of emergency or failure of the air supply.

An important feature of the hoist consists of means for automatically applying the brake in case the supply of currrent to the hoist motor fails. This consists of an alternating-current solenoid, energized from the supply circuit through a potential transformer, so arranged that when the solenoid circuit fails the core of the magnet drops and actuates an air valve on the brake cylinder, allowing the brake to be set as usual by gravity.

The plan and profile of the mine where this hoist is installed, as developed at the time of installation, is illustrated in Fig. 3. It will be noted that a uniform grade of approximately 7½ deg., and 676 ft. (206 m.) in length, reaches from the surface to the knuckle, and that the slope beyond the knuckle varies, but is approximately 25 to 30 deg., although local faults may increase this grade materially at points. Branch headings are designated as " first left," " first right," " second left," " second right," etc. These headings may eventually be developed to a length of from one-quarter to one-half of a mile, (402 m. to 804 m.), or until met by similar headings from an adjacent mine.

The track of the mine is 42-in. (1.07 m.) gage, and standard mine cars weighing 2500 lb. (1134 kg.), empty, are used. As many as five cars are hitched in train and each may be loaded

FIG. 1 [CHENEY]

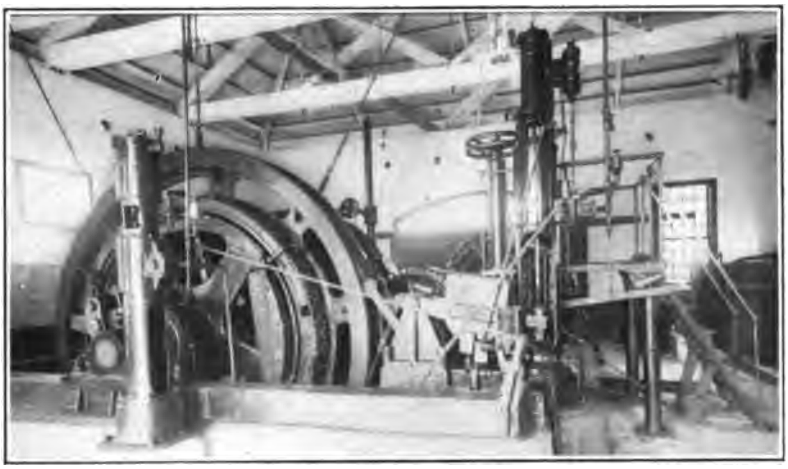

FIG. 2 [CHENEY]

FIG. 4 [CHENEY]

with approximately four tons* of ore, making a total load, including cars, of 52,500 lb. (23,813 kg.).

The track curves at the branch headings are very sharp; in most cases the radius does not exceed 8 ft. (2.4 m.). By reference to the plan and profile of the mine, it will readily be seen why the highest peak of the hoist load occurs as the loaded cars are being pulled around this sharp curve onto the incline. Often loaded cars become derailed at this point, owing to the sharp curve, and must be pulled onto the track at the curve. It is this contingency that calls for the greatest effort on the part of the hoist and draws the greatest amount of power from the transmission line.

The tipple shown in Fig. 4 is of more than passing interest, and consists of a rotatably mounted cylindrical framework into which the train of mine cars is drawn. The wheels of the cars run under a supplementary rail in the framework which maintains the relation of the cars and track while dumping. The ore cars are automatically dumped by the rotation of the cylinder, which is accomplished by means of compressed air under the control of the operator. A large sheave is placed at the outer extremity of the tipple over which the wire rope is carried from the drum of the hoist and attached to the mine cars. This rope also passes over wide sheaves or rollers at intervals along the track during the descent of the cars into the mine, thus relieving the friction and wear of the rope. During the hoisting operation, as the cars approach the tipple they are stopped for a moment at the weighing platform shown in the cut, where each trainload of ore is

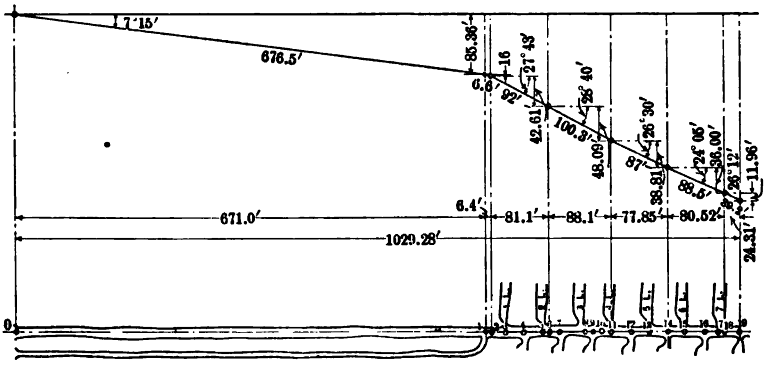

FIG. 3

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*One long ton = 1.016 metric tons.

weighed and recorded. After being dumped into the huge hopper underneath the tipple, the ore, which is in the form of rock, passes through the crusher into the cars which are used to haul it to the blast furnaces.

Only two men are required at the surface during regular operation: the hoist operator and the weigher.

The hoist at this mine is approximately four miles from the power house of the company, and electrical energy is transmitted at a voltage of 3300 and a frequency of 25 cycles over a three-phase system.

The hoisting engine and the electrical control equipment are housed in a brick building which is located on the slope of the hill just above the mine entrance.

The 3300-volt lines are brought into the hoist house and connected to high-tension busbars. Two switchboard panels are installed, consisting of the main motor panel, upon which are mounted an overload no-voltage release oil switch and an ammeter with a current transformer, and a line panel, upon which a non-automatic oil switch, an ammeter with a current transformer, and three three-pole single-throw fused knife switches are mounted.

Three transformers of 50 kw. capacity, having a ratio of 3300 to 220 and 110 volts, are connected in delta to furnish energy for lighting, for running an electrically-driven air compressor used as an auxiliary, and a circulating pump for the liquid rheostat. An electrolytic lightning arrester is also installed for protection against lightning disturbances, which are frequent in the locality of this installation.

Fig. 5 shows a diagram of electrical connections of the control system. Referring to this diagram, the electrical operation of the hoist is as follows:

The non-automatic oil switch on the transformer panel is first closed, thus exciting the transformers. The three-pole single-throw knife switches on the same panel are then closed, supplying alternating current at 220 volts to the motor of the water circulating pump, to the air compressor motor through a pressure regulator switch, to the no-voltage coil of the main oil switch on the motor panel, and to the terminals of a switch connected to the brake solenoid. This latter switch is mechanically connected to the overload no-voltage release oil switch so that both are opened and closed simultaneously. The overload no-voltage release oil switch is now closed and the hoist is ready for regular operation from the hoist platform. It should be stated that in the oil switch used, the overload coils are direct series trip coils, and the overload and no-voltage coils act independently of each other on the mechanism to trip the switch. A forward movement of the operator's control lever closes the primary switch making final connection to the primary winding of the induction motor for hoisting, while a reverse movement of the same lever closes the primary oil switch making reversed connection with the primary winding of the motor for lowering. It is necessary to provide the reversing feature, since the slope of the mine near the entrance is not sufficient for empty cars to unwind the drum of the hoist by gravity.

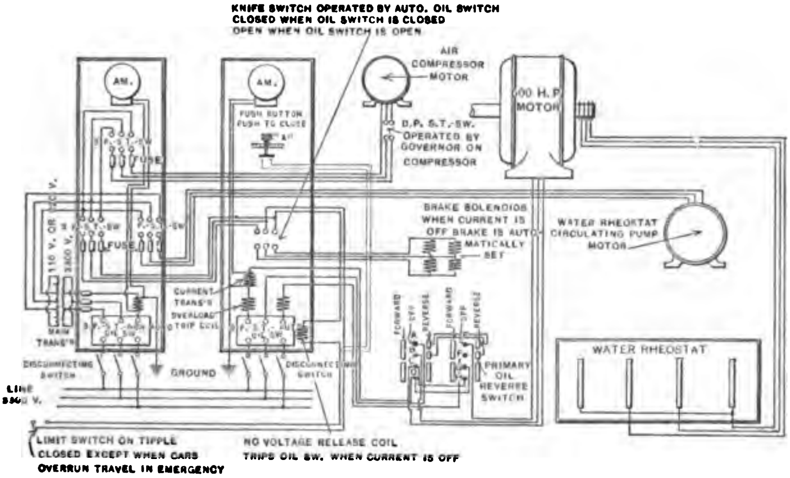

FIG. 5

The secondary windings of the motor are connected to the terminals of a liquid rheostat for varying the resistance of the secondary circuit and controlling the speed of the motor. The operation of this rheostat is controlled by the same lever that is used to open and close the primary switch. The details of construction of the lever mechanism will be explained later.

Particular attention is called to the limit switch. This switch is placed on the tipple in such a position that if the cars overrun it will be mechanically opened by a track lever. The circuit of the no-voltage release coil of the main oil switch passes through this limit switch, and in case the car passes the limit of travel the oil switch and solenoid brake switch are automatically opened, thus cutting off the motor current and automatically setting the brake regardless of the position of the operator's handle. In case of overload or short circuit sufficient to trip the oil switch, the brake is also set by the means above described.

A push button which is normally open is provided on the motor panel for closing the circuit of the no-voltage release coil of the oil switch after the cars have overrun in order to back them into position again for regular operation. This is purposely arranged so that an extra man will have to be called upon to help the operator after an automatic stop at the tipple has been made. This provision was made so that carelessness at this point would be reduced to a minimum on account of the inconvenience caused by it.

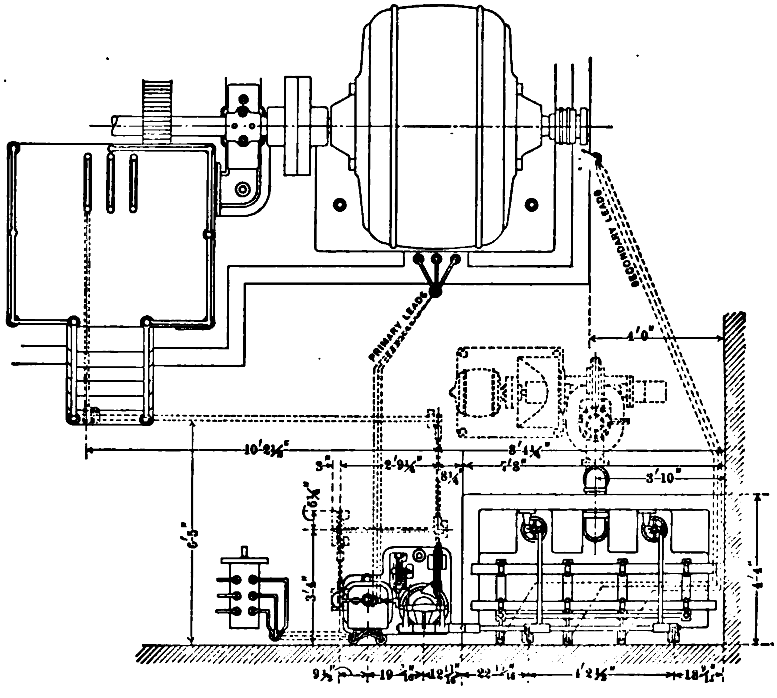

Fig. 6

Another safety feature worthy of notice is a provision for the automatic opening of the overload no-voltage oil switch in case the non-automatic transformer switch is opened, thus cutting off supply current to the auxiliary apparatus, and also making it impossible to hold the overload no-voltage switch closed unless the non-automatic transformer switch has first been closed.

The general layout of the controller in its relative position to the cage of the hoist is shown in plan in Fig. 6, and in elevation in Fig. 7. The controller consists of a primary switch for closing, opening and reversing the 3300-volt primary connections to the motor, and a liquid resistance in the secondary circuit of the motor to limit the line current for the required torque at starting and for speed regulation during regular operation.

The primary switch is oil-immersed and is of the rotary multiple-break type. It is so arranged that when turned in a clockwise direction from the off position connections are made for forward rotation of the motor, while if turned in the opposite direction the motor is reversed.

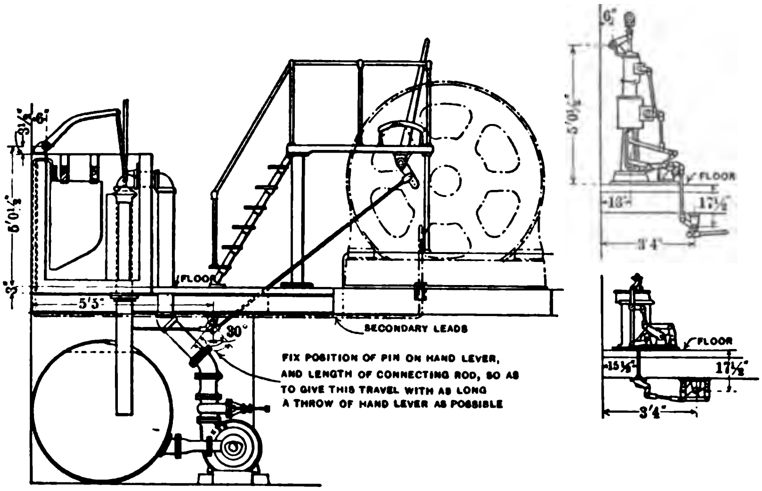

FIG. 7

The liquid rheostat for the secondary circuit is shown in detail in Fig. 8, and consists of a concrete tank in which stationary plates of cast iron are suspended as electrodes. Electrolyte is then raised or lowered in the tank by mechanical means to vary the resistance between the electrodes. The electrodes are hung on insulating supports which are set in a recess in the concrete tank near the top. They are ribbed to give maximum contact area with a minimum amount of space and are made of a special form which was carefully worked out to give a smooth speed and accelerating curve. Four electrodes are used for the three-phase circuit, the two outer ones being connected together and to one phase. By proper spacing, which was determined by preliminary test, the correct amount of resistance and a balanced three-phase star-connected resistance is obtained at all times. By the use of ribbed angle plates, which are bolted to the electrodes near the top, and which overlap each other with a small intervening space, the effective distance through the liquid between plates is gradually decreased, and the effective area of the plates is gradually increased, as the liquid is raised in the tank. At the highest level of the liquid the plates are practically short-circuited by the electrolyte which flows in and fills the small space between the horizontal portions of the angle plates.

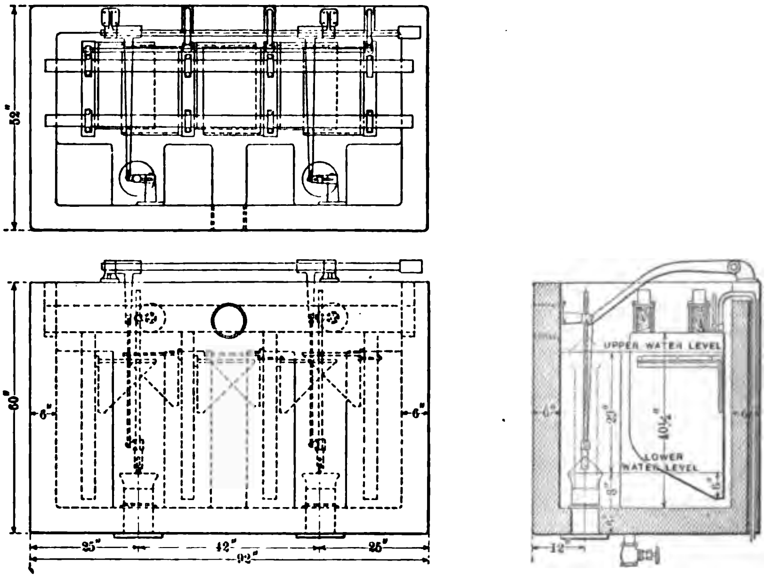

FIG. 8

The electrolyte used consists of ordinary well water in which a small quantity of salt was dissolved. The amount of salt which gave the bests results with the water used in the liquid rheostat where this hoist was installed, was found to be nine pounds of salt per one thousand gallons of water, or approximately one-tenth of one per cent by weight.

A cooling tank is located in the basement directly under the rheostat tank, and a centrifugal pump serves to pump the liquid from the cooling tank into the rheostat tank and to keep it in continuous circulation. This pump is driven by a 220-volt squirrel-cage induction motor and is run continuously. A gate valve is placed in the discharge pipe of the pump to regulate the rate of flow into the rheostat tank.

The height of liquid, and consequently the amount of resistance in the secondary circuit of the motor, is regulated by means of two movable weirs in the form of pipes which are raised or lowered through an opening near the bottom of the tank. By the use of the pipe construction for the weirs, all friction, due to side pressure of the liquid, is eliminated. The arrangement is such that all of the liquid cannot escape through the weirs when in their lowest position. The lower ends of the electrodes are thus always immersed and the secondary circuit is never opened. The total area of the openings through the weirs is approximately double that of the inflow pipe, and is sufficient to allow the maximum amount of liquid in the rheostat tank to escape into the cooling tank in ten seconds, including the continuous discharge from the pump. With the gate valve wide open and the weirs raised to the highest point, the rheostat tank will fill in approximately 20 seconds. This time may be increased as much as desired by adjusting the opening of the gate valve.

All of the metal parts inside of the tank, with the exception of the cast iron electrodes, are heavily galvanized to prevent deterioration from rust.

Since compressed air is utilized for actuating the clutch and brake mechanism of the hoist, the control mechanism was designed for air operation throughout. A double-acting air engine is connected to the weirs through a rocker shaft and levers and to the primary oil switch through a reversing clutch in such a manner that the first part of the upward piston stroke closes the oil switch, and a continuance of this movement raises the weir. This engine is provided with an adjustable oil cataract and a floating lever valve device, by means of which the air piston may be stopped and held at any point corresponding to the position of the operator's lever.

The operator's lever, which is located on the cage or platform of the hoist, rests at the central point of a notched sector when the controller is at " off " position. When the lever is moved away from the operator, the first movement sets the clutch on the primary oil switch for clockwise movement of the rotating member of the switch, and a further movement of the lever opens a valve and admits air to the air cylinder, which first closes the switch and then raises the weirs to any desired height. To stop the motor the lever is returned to the "off" position. A mechanical interlock is provided at this point to prevent the operator from throwing the lever to reverse position until the weirs reach the lowest point and the maximum secondary resistance is inserted. In case it is desired to run the hoist motor in a reverse direction, the operator's lever is moved toward the operator, when the clutch on the primary switch is first set for counter-clockwise movement of the rotating member of the switch, and the rest of the operation is the same as before described, except that the motor runs in the reverse direction.

The by-pass of the oil cataract on the air piston is adjusted for the maximum allowable piston speed at which no jar or shock to the mechanism occurs when the operator's lever is thrown quickly from one extreme to the other. The gate valve is set for minimum time of acceleration for a given primary current with an average load of ore on the average grade. Semi-automatic acceleration is thus obtained; that is, if the operator throws his lever to the extreme position, the acceleration of the hoist is automatic and will be accomplished in as quick a time as can be done without too heavy a draft of current from the line, while if it is desired to regulate the rate of acceleration the operator may allow the operating handle to remain at any intermediate point between the off and the full-speed position, which allows regulation anywhere inside of the limits for which the controller is set.

During the tests which followed the installation of this controller, every conceivable movement that could be given the operator's lever was tried, and it was found that no damage whatever could be done to any part of the outfit by improper manipulation of the control lever.

Owing to the lack of reliable data from the experience of others, it was found necessary, before designing this controller, to make preliminary tests to determine the necessary data to be used. A large number of tests were made to determine the proper surface area of electrodes per ampere of current. It was found that with alternating current two amperes per square inch could be used as a fair average, and that the area could be varied between one ampere per square inch for continuous service and three amperes per square inch for intermittent service without undue deterioration of electrodes or excessive generation of gases.

Tests were made to determine the inches per volt drop at different temperatures for different solutions. Fig. 9 shows a typical curve obtained for a 5.4 per cent solution of common salt (NaCl) in distilled water, by weight, and also for a solution of caustic soda ($NaHO_4$). Curves were also consulted for solutions of sulphuric acid (H_2SO_4), caustic potash (KHO), sodium sulphate (Na_2SO_4), and copper sulphate ($CuSO_4$), but the conclusions reached were that good average results could be obtained by the use of common salt solution and that its use would be preferable for a mine hoist controller on account, more particularly, of the ease with which it can be obtained and on account of its mild action on the metal electrodes and piping.

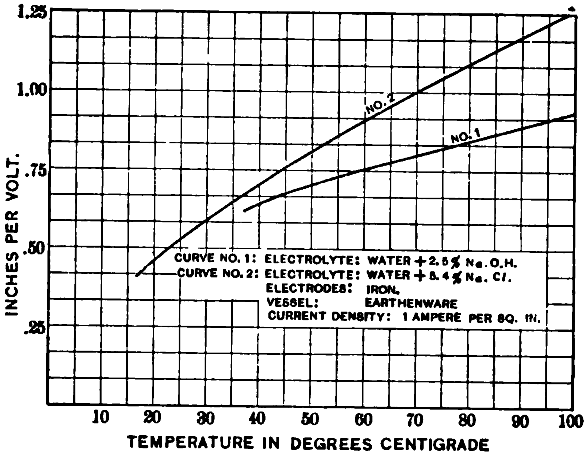

Fig. 9

A series of tests was made to determine the most feasible arrangement of plates to obtain balanced three-phase resistance and at the same time to conserve the volume of the rheostat tank. Several schemes were proposed and tried, and while a number of different arrangements were found which gave perfect balance, the one shown in Fig. 10 was adopted as being best suited to a tank of rectangular construction, and saving of space.

While, theoretically, the watts dissipated at a given temperature depend upon the surface area of the liquid and not upon its volume, experiment demonstrates that calculations based on watts dissipated per cubic inch (16.4 cu. cm.) of liquid are more reliable and may be followed with the best results in actual practise. Fig. 11 shows a curve giving the approximate rise in temperature which may be expected for from one to four watts dissipated per cubic inch (16.4 cu. cm.) of solution.

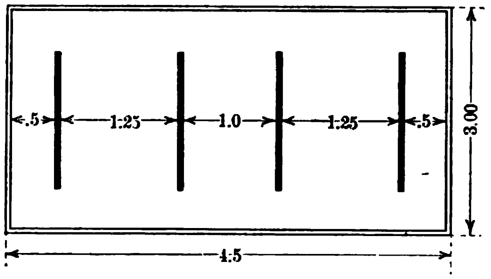

Fig. 10

For the purpose of making tests on the hoist and controller a portable instrument rack was constructed, upon which were mounted a graphic recording polyphase wattmeter, a graphic recording ammeter, a graphic recording speed indicator, two indicating voltmeters, two indicating ammeters, and a polyphase integrating wattmeter.

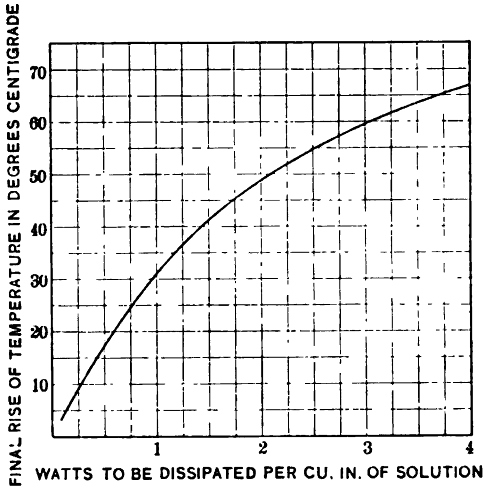

Fig. 11

Owing to the time of the hoisting cycle, it was necessary to speed up the record strips in the recording instruments to about

6 in. (15 cm.) per minute. This was done by driving the instruments through a countershaft by means of a small synchronous motor mounted upon the rack. The recording speed indicator consisted of a voltmeter connected in circuit with a magneto driven by the hoist motor. The recording wattmeter, ammeter, and the integrating wattmeter were connected in the primary circuit of the hoist motor and the indicating voltmeters and ammeters were connected in the secondary circuit. Two recording or integrating wattmeters, which are unaffected by frequency changes, and which are reasonably accurate over a wide load range, were connected in the secondary circuit of the hoist motor.

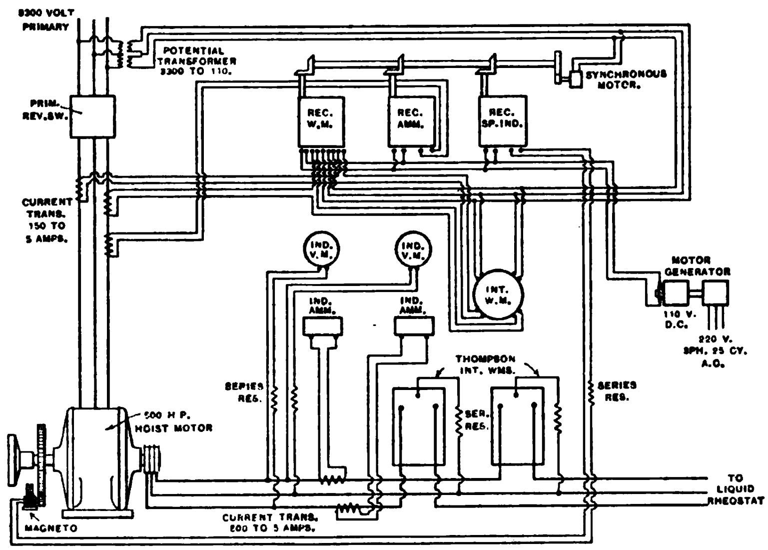

FIG. 12

Observations as to line voltage, frequency, etc., were made upon the regular switchboard instruments.

A diagram showing instrument connections used in making tests is shown in Fig. 12. All instruments were carefully calibrated in the factory laboratory preparatory to the test.

Readings were made and records taken on a large number of complete trips during regular operation of the hoist soon after its installation. No special preparation was made in the mine in regard to loads and heights of lift, but accurate records were kept of the weights of each load and of the heading of the mine from which it came. The hoist was operated during the test by regular employees of the mining company, who were at that time unaccustomed to the use of electric hoists. The track had been relaid to a wider gage and new cars of greater capacity had been installed when the operation was changed over from steam to electricity. The track and cars were consequently in good condition.

Fig. 13 shows typical graphic meter records giving kilowatt input, primary amperes and speeds during one complete cycle of 8¾ minutes, and from the No. 4 left heading, with a five-car load weighing 37,700 lb. (17,100 kg.) gross, or 25,200 lb. (11,430 kg.) of ore, net.

Based upon data obtained from this curve and from the observations taken during the trip, which represents a fair average

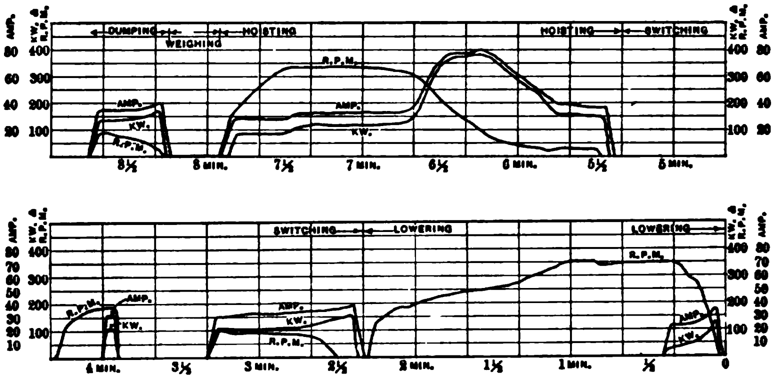

Fig. 13

of the regular performance of the hoist at the time the tests were made, calculations show the combined efficiency of the hoist and controller during the hoisting period to be 36.7 per cent.

From the records of these tests exact information is available as to the watt-hours input per ton-foot of ore hoisted, energy output and actual work done, percentage of loss of the liquid rheostat controller and total combined efficiency of the entire outfit.

The nature of the work to be done in electrical hoisting is so varied and conditions encountered are so different in different mines, that a hoisting equipment which is entirely suitable for one class of work may be out of the question on another class of work.

In a great many cases the efficiencies, so far as actual consumption and energy input are concerned, are a secondary consideration to the speed of operation, continuity of service, reduced manual labor, reduced maintenance cost, and reduced initial cost of the hoisting equipment.

In each case conditions must be very carefully studied to determine the type of hoist most suitable for the work in order that the total operating expenses for a given result may be as low as possible, and in order that the initial expense of the equipment may not be prohibitive.

It is a well-known fact that rheostatic control of electric motors, whether used for alternating or direct current, is inherently inefficient. There are, however, innumerable places where the fact remains that it is good engineering to employ this form of control owing to simplicity in design and operation.

Where it is desired to employ alternating-current induction motors for hoisting operation, rheostatic control is necessary in order to regulate properly the speed of operation. The use of such motors for hoisting service is increasing, due to low maintenance cost, low initial cost of plant, and reliability of service obtained.

The extremely smooth acceleration obtained with the liquid rheostat, which is not possible with other types of control, is of inestimable value in mine hoisting. It is possible to move the rope a foot or two very slowly and without jerks or sudden impulses. This is of great advantage in taking up the slack in the rope and in pulling the loads out of the branch headings. Practical operation has demonstrated that there are very few wrecks inside of the mine employing this form of control as compared with the numerous wrecks had in adjacent mines where steam hoists are used.

In conclusion, it is the belief of the writer that the liquid rheostat type of control offers possibilities which have not received warranted attention in this country, and that with proper development along this line a highly satisfactory solution is available for the problems encountered in the control of electric mine hoists, especially those employing alternating-current induction motor drive.

DISCUSSION ON "ELECTRICAL CONTROL OF A LARGE MINE HOIST" (CHENEY), PITTSBURGH, PA., APRIL 27, 1912.

H. M. Gassman: I have had an opportunity to examine critically this installation. I can confirm all that Mr. Cheney has said in regard to the operation. I wish to emphasize particularly the smooth acceleration obtained. There was absolutely no noticeable jerking or impulse given to the rotor in starting with this type of control. Furthermore, I made it a special point, from the operating end, to inquire into the maintenance of this type of starter, and I was told by the man responsible for its operation that it is practically nothing.

W. O. Oschmann: Is the air clutch for any purpose other than allowing the cars to drift into the mine when the hoist motor is stopped, and is the maintenance of this clutch excessive?

I would also like to know if a slack cable device is used on this hoist which will automatically stop the hoist when cars are being lowered into the mine, if for any reason the cars become derailed or are otherwise accidentally stopped.

H. E. White: The paper presented by Mr. Cheney is of unusual importance in that it shows clearly the possibilities of a type of control hitherto little used in this country, but which is in Europe a recognized standard for large induction motors driving mine hoists.

One is greatly impressed with the simplicity and reliability of the whole thing as compared with the systems of control with magnetic switches which are the nearest equivalent. About the only adjustment requiring care is the maintenance of the proper saturation of the electrolyte, and this would not seem to be very difficult. Some losses in the water would occur, but these could readily be noted and the deficiency made up.

It is to be presumed that Mr. Cheney is familiar with some of the means which are in use elsewhere whereby a very quick emptying of the tank can be accomplished. In the application described this does not seem necessary, but in some cases the time of emptying, given as ten seconds, would be too slow. An almost instantaneous emptying is sometimes secured by using weirs that cover all of one side of the tank and which can be lowered very quickly to allow the electrolyte to escape. This arrangement would be necessary where a quick reversal of the motor is required. The use of compressed air as described in Mr. Cheney's paper would seem adverse to the very quick opening of the weir. The quickest results could be secured where the weir is carefully balanced and is controlled directly by hand. When properly made such a weir will not require a very great manual effort.

In designing a water rheostat there is some difficulty in getting proportions that will result in a small slip at full load, it being impossible to reduce the minimum resistance quite to zero.

Considering the other advantages this should not be serious enough to lead to its rejection.

In conclusion the writer wishes to express his belief that the water rheostat will meet with greatly increased use in this country.

Wilfred Sykes: The application of the brake by means of a solenoid which will open the air exhaust is the usual practise with European manufacturers, and to my knowledge it has been used since 1900 as part of the regular equipment of two principal European electrical manufacturing concerns.

Mr. Cheney drew particular attention to the limit switch, and I would like to point out that limit switches on any alternating-current hoist to trip when the cars pass a certain point are useless as far as concerns protecting the equipment against damage. The reason is that in order to allow the cars to approach the surface or the tipple at a slow speed the limit switch must be set beyond the dumping point. If for any reason, however, the operator fails to cut off the current from the motors and the cars are running, as in this case, practically on level track, the inertia in the moving part is sufficient to carry them on to the head sheaves. From the illustration it appears there is not a very great travel allowable beyond the dumping point, and if the operator should fail to cut off the current at the right place or slow down properly, it is possible to wreck the whole outfit. To overcome this, a patent has been taken out in England for a device which arranges the control in such a way that if you do not slow down at the proper rate, when you are approaching the surface, the brakes will be applied; assuming you start to slow down 50 ft. from the surface, and you run that distance at rather high speed, the brakes will come on before the cars reach the surface. On the other hand, if you slow at the proper rate, the prescribed rate, this apparatus does not come into play and nothing happens.

In the description of the liquid controller, and it seems to me that this is the principal item in this hoist, it is stated that the electrode tank is concrete lined. I would like to ask why that is done. An experience over a great many years, with a liquid starter, has demonstrated to me that if you do not have an electrolyte that is corrosive a plain iron tank is very satisfactory, and I know of a great many starters that have been used for seven or eight years, and there has been no trouble from the tanks being eaten through.

It is not quite clear why the electrodes were arranged in the way they are, with cross plates between them in order to increase the area and reduce the effective distance between them. It seems to me the obvious arrangement is to have a number of vertical plates, and you can have these of different lengths, so that as the liquid rises the resistances are readjusted in the proper way. It is not necessary to have the electrodes so far apart as shown in Mr. Cheney's paper, nor, in my opinion, is it necessary to work with this low current density. I have repeatedly run liquid starters in which the electrodes were not more than a half-inch apart with current densities up to ten amperes per square inch, and you can do that for short periods, such as will be required in the acceleration of a hoist of this kind, provided you have the forced circulation and the liquid flows rapidly between plates. If you have a stationary liquid, and no forced circulation, then you cannot run the density so high, but there is no difficulty in running it up to 10 amperes per square inch for other purposes. Usually, it is a good deal lower than that.

I would like to ask why salt is adopted. My experience has been that common washing soda or carbonate of soda is about the most satisfactory electrolyte that can be obtained. It is cheap, and a good many tests have shown that the corrosion with this electrolyte is a good deal less than with anything else you can obtain. I would like to refer to some tests published in the *Electrotechnische Zeitschrift*, about four years ago, which go very completely into the question of corrosion of the electrodes with different electrolytes, both for direct current and alternating current.

This apparatus seems to me to be very large for the amount of work intended to be performed. There is no dimension given of the size of the cooling tank. As far as I can judge, it seems to be five feet wide, but the length you cannot tell; but for the amount of energy that has to be absorbed by this starter, this seems to be very large indeed, especially the electrode tank. I have repeatedly started motors up to 1000 h.p. on starters in which the electrode tank was only about 24 in. square, and the electrodes immersed about fifteen inches in the water. As a matter of fact, with some of the European concerns, it is more or less standard practise to have that proportion. You can run the starter much harder when you have forced circulation than you can in this case.

The question has been raised as to the time required to empty the tanks. No doubt in this installation the quick emptying of the tanks was not necessary, but if you have a vertical hoist where it is quite often necessary to plug the motor in order to protect it, you must be able to empty the tank almost instantly, and I should set a limit of not more than two seconds as about the maximum which you can stand for any vertical hoist in order to obtain proper control. It would be absolutely out of the question for it to be necessary to take 10 seconds for any fast work. In this case probably 10 seconds is all right for a slow hoist.

The last discussion I think pointed out that in order to get quick operation of your hoist the best arrangement would be to have the weirs manually operated. I think if you design the starter properly you can work this all right. The addition of air cylinders and the various lever arrangements described certainly must increase the cost of the starter quite appreciably, and also it gives so many parts that may possibly give trouble.

Mr. Cheney stated that there was very little information available when he started to design this controller, regarding liquid starters. There is a good deal of information, however, which has been published in the German papers like the *Elektrotechnische Zeitschrift*. There have been quite a number of articles in that publication on this subject, and they have given a large amount of detail information as to the practise of various European manufacturers.

Regarding the question as to the capacity of the rheostat, which Mr. Cheney pointed out—in this case they used the number of watts that could be absorbed per cubic inch—my experience with a starter of this kind has been that the energy absorbed is taken care of by the evaporation of the water, and if you have forced circulation with an open electrode tank as you have here, you can put in about two or three times as much energy for the same volume of water, the same temperature rise, as you can if you have not the forced circulation.

Of course, if you have cooling coils you can practically take care of almost the whole of the energy in the cooling water, although, in such case, when you are pushing the rheostat very hard, a great deal of it is lost by evaporation, but it does not necessarily mean that a great amount of water is evaporated, on account of the fact that if you evaporate water it takes something like 900 B.t.u. per lb., which will take considerable energy.

Mr. Cheney stated that the rheostat control was inherently uneconomical in the place where it is, but not always for hoist work; in fact, in a great many cases, especially where the hoist is only worked to a limited extent, or where the hoist speed is low, or the accelerating period is comparatively a small percentage of the total running period, then the rheostatic control will be found to be the most economical that you can have for a hoist. Where you have very rapid operation, high speed and short lift, then some other system, such as the flywheel motor-generator system, or just the plain motor-generator system with voltage control, would probably be more economical; but generally it will be found that the rheostatic control is the most economical arrangement for the average hoist.

F. L. Stone: I have read with considerable interest Mr. Cheney's paper on the control of a large mine hoist, and there are several points which I would like to discuss. Mr. Cheney states that the design of hoist apparatus must be such as to withstand most severe and unreasonable conditions of service. I cannot understand, when the duty cycle is given, why there should be any difficulty in the proper design of the control and hoist motor. It seems to me that we know more about the loads to be imposed on a hoist motor than almost any other line of motor application, and therefore, when the proper use of this knowledge is made, there should be no failures in electric hoisting.

In regard to the particular hoist described, Mr. Cheney advised that the gearing was the triple reduction type. The gear reduction from the motor to the drum is only 8.5:1 and could be economically obtained by one reduction. If there are three reductions as stated, I would like to inquire why, since this must of necessity make the friction losses excessive.

In regard to the design of the liquid rheostat proper, I note there are but four plates used, and to these plates in the upper ends are bolted additional plates for increasing the area of contact, and that the plates proper are made of cast iron. With this arrangement I can readily conceive the difficulty of having the phases balance during the acceleration period. Would it not be better to use a multiplicity of plates in parallel on phases, such as, say, twelve or fifteen? This reduces the chance of unbalancing the phases very materially and gives a very large area of contact. These plates can be tapered if so desired.

I further note that it takes 10 seconds to empty this tank and approximately 20 seconds to fill it. It would seem to me that if quick reversals were called for in emergency conditions, this slow emptying of the tank might produce very injurious results, as the motor would be reversed to the very lowest resistance in secondary.

I note further that sodium chloride had been used in the electrolyte. Experience has shown that the use of sodium carbonate gives much better results in that there is no active gas such as chlorin liberated, and the life of the plates is much prolonged. I might further ask why cast iron plates are used in the place of sheet steel, the latter being much more readily renewed.

Fig. 13 shows the operation of this hoist very clearly and there are several features in connection with these curves about which I would like to ask information. First, I note from the revolutions per minute curve that it takes approximately 60 seconds for the hoist to reach running speed. This would seem to me an excessively long time to accelerate such equipment. Further than this I note that the hoist does not reach running speed until the trip is past the knuckle and the load fallen to approximately 125 kw. It would seem to me that this points to excessively high resistance in the liquid control. This point is further exemplified by the fact that, from the revolutions per minute curve, the slip in the motor, due to the resistance of the controller and the resistance of the rotor, is approximately 10 per cent with only 100 kw. output. This further points to very high resistance in the control. Liquid rheostats are working satisfactorily with but 5 per cent slip at full load, of which approximately 2½ per cent is due to control resistance and 2½ per cent due to rotor resistance.

I note that the maximum speed called for is 750 ft. per minute, while the average speed, as closely as I can determine from the curve, reached 450 ft. per minute. This means slow production.

I would be glad to hear Mr. Cheney's comments on these points, as they are of vital interest to electrical designers. The liquid controller is becoming more and more popular daily and within the next two years there will be a great many of them installed in this country.

Wilfred Sykes: There was one point I intended to mention, and that is the specific resistance of the electrolyte is practically of no importance, because if you have the distance between the electrodes properly arranged in the right proportion it does not make very much difference what the specific resistance of the electrolyte is; because this can always be arranged by adding more or less salt to the water. In fact, you have to do that anyway, because you cannot get any fixed formula for the amount of salt required, owing to the variation of the water in different localities, so that the main thing in the designing of a starter of this kind is to get the areas and proportions of the electrodes right.

E. Friedlaender: I wish to ask how much the efficiency of this installation could have been increased by using a smaller motor which would have done the work just as well.

H. W. Cheney: In reply to Mr. Oschmann's question, I will state that the air clutch is simply used to disconnect the drum from the driving members of the hoist to allow the cars to lower into the mines. There is no slack rope switch provided in this installation.

Mr. White points out that the quick opening of the weir is sometimes desirable. Mr. Sykes also mentions this point. In quite a good many installations, I agree, it would be extremely important that an opening through the weir or possibly an auxiliary opening be provided, so that the electrolyte can escape very quickly.

Mr. Sykes mentions a limit switch and states that in an installation of this kind a limit switch would be practically useless. As a matter of fact, I know that the limit switch has in several instances operated and has stopped the hoist in a very short distance. I do not know that it has operated at the extreme outward travel of the tipple, but I am informed by the men down at the mine that the limit switch has proved satisfactory. I have not been on the ground, of course, to see just what did take place.

Mr. Sykes mentions concrete and wants to know why concrete was used. As a matter of fact the concrete was adopted, not because it was a particularly better design than any other material, but partially because the people who were installing this apparatus were willing to build the tank right in the hoist house, and we did not see any reason why the concrete would not be satisfactory, and it has proved satisfactory in operation.

Mr. Sykes mentions that he has had experience in operating liquid rheotsats of up to 10 amperes per square inch. That is quite possible, that is, for intermittent periods; and I think that it was not the intention of this paper particularly to limit the amperage to three—of course, we should be guided by the nature of the intermittent service. I have said from one to three amperes—one ampere for continuous service, and three amperes for intermittent service. Intermittent service is a term which may have one meaning in one case and may have quite another meaning in another case. If the service is quite frequent, then I would say it is better to hold the area, that is, the amperes per square inch, down to somewhere near the limit given.

Mr. Sykes also asked why salt was adopted. I believe I mentioned in the paper that we found a number of different solutions which would probably be satisfactory, but that we adopted salt because we found that it worked satisfactorily and it was readily obtainable, and people are familiar with it, and they are always able to get salt when it is sometimes impossible to get some of the other materials.

I wish to say, in regard to the electrode tank being large, that I agree with Mr. Sykes that this tank might have been made smaller. This was the first liquid rheostat that I have had anything particular to do with in the way of designing a controller for regularly operating a large induction motor, and I have found, since the installation of the apparatus, that we were on the safe side by a considerable amount. We might have made the tank smaller.

In regard to operating the weirs manually, I would also say that that can be very readily accomplished, in fact, it is being accomplished in other later designs. This plant was designed some time ago, and the description given in the paper, while it is not intended to show the latest design for controllers of this type, was intended to show a type of liquid rheostat that has proved very satisfactory. I quite agree that the forced circulation of water through the rheostat tanks increases the capacity of the electrolyte to absorb energy.

With regard to Mr. Stone's point, of course it is quite impossible to cut out all of the slip with this form of controller, and where the controller is running for a large portion of the time at somewhere near full speed it would also be quite desirable to provide means of short-circuiting the rings of the induction motor in addition to the final point of the liquid rheostat. That can be easily accomplished by an auxiliary switch. However, in this particular installation the trips at the present time are comparatively short.

Mr. Friedlaender asks why a smaller motor could not be used. As shown from these curves it would appear that a much smaller motor might have been used. As a matter of fact this mine, at the time these tests were made, was not developed to anything like the extent that it will be developed, we expect, in the future.

As the depth of the mine becomes greater, it is anticipated the load will be increased materially. The motor we have found to be satisfactory and amply large, but in line with the discussion of some of the papers yesterday, we prefer to be on the safe side in specifying motors of sufficient capacity to take care of the heavy loads which are obtained in pulling up around the curves when the loaded cars become derailed.

M. A. Whiting (communicated after adjournment): In answering the criticism of the high slip (and consequent low efficiency) at full speed, Mr. Cheney stated that where the period of full-speed running is long it will be advantageous to short-circuit the motor secondary at the brushes by means of switches. It is extremely doubtful whether any simple and wholly reliable method can be obtained whereby contactors (or other forms of switches) can be used to short-circuit the rheostat automatically when the liquid rises to its maximum level.

Provided that some means can be found for accomplishing this, there still remains another point to consider, viz: the fluctuation of load when the rheostat is short-circuited. In the installation under discussion (see Fig. 13 in the paper), the maximum hoisting speed is 335 rev. per min., representing 10 per cent slip at a load of approximately 135 h.p. (27 per cent rated load). For a motor of this size, of normal design, the full-load slip with brushes short-circuited may be assumed to be approximately 2½ per cent. Now with the motor running at 10 per cent slip, to short-circuit the motor secondary at the brushes will cause an instantaneous peak of about 250 per cent of rated torque and rated current, *i. e.*, the fluctuations of torque and current will be of a magnitude equal to approximately 200 per cent of rated load. On the other hand, if this equipment were called on to deliver rated load at full speed (*i.e.*, with minimum resistance of the liquid rheostat), the slip would be about 35 per cent, and to short-circuit the liquid rheostat under this condition would obviously be out of the question.

It might be considered possible to short-circuit the liquid rheostat in several steps by means of an ordinary rheostat to be thrown in multiple and cut out in steps. Such an arrangement, however, necessitating several contactors, accelerating relays and a device for interlocking with the liquid rheostat, all in addition to the liquid rheostat itself, would be entirely too complicated to merit serious consideration.

The only proper remedy for the high slip and consequent poor full speed efficiency revealed by Fig. 13 is, therefore, to use a liquid rheostat with a much lower minimum resistance. Liquid rheostats have been built (at lower costs than required for equivalent secondary control equipments using contactors), in which the slip introduced by the rheostat is not more than 4 per cent at full load.

Louis C. Marburg (communicated after adjournment): This paper is of particular interest on account of its description of a type of control still unusual in this country. The writer wishes to join most emphatically with Mr. Cheney in his statement that liquid rheostats have not found in America the attention they deserve.

It is a fact known by all those that observe developments in various countries, that invariably it takes a number of years before improvements made in one country are adopted in other countries. However, the liquid rheostat has surely had more than its due share of waiting in this country before it has found even the slightest favor. Let us remember that the locomotives of the well-known Lecco-Collico-Chiavenna three-phase line in Italy, which was in operation as far back as 1901, use liquid rheostats in regular operation and that innumerable control equipments of this type have been installed in Europe during the last ten years.

Among the most interesting examples were two large liquid type controllers installed at a mine near Essen, Germany, some years ago, for use in connection with two large Ilgner motor-generator sets. When the writer visited the plant in question for the first time, large and extremely expensive control equipments of the metallic resistance type were trying to take care of the large induction motors. They were entire failures and upon his next visit the writer found them replaced by liquid rheostats and everybody was happy.

In advocating these equipments in this country the writer has found rather general opposition. When the hoisting equipment described by Mr. Cheney was constructed, the writer was connected with the company that built this hoist and was in charge of electric hoisting equipments. To convince the customer regarding the merits of liquid rheostats which to the writer, in view of European experience, appeared the only feasible control, was not so difficult. With his own company, however, the writer encountered a general disbelief that the equipment would ever be a success and there were many to prophesy certain disaster. It is only this attitude, which was in line with a dislike of the liquid rheostat still general among engineers, that makes it worth while to call attention to the successful operation of the equipment.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 27, 1912.

NOTES ON THE USE OF ALTERNATING CURRENT IN UNLOADING COAL

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The receipts of coal in Duluth-Superior Harbor increased from 2,600,000 tons* in 1900 to 8,300,000 tons in 1910. This coal comes principally from Pennsylvania and West Virginia and is brought by rail to Lake Erie ports where it is loaded into boats for transportation to Duluth and Superior. Of the receipts in 1910, two million tons were anthracite and the remainder bituminous coal. At Duluth-Superior Harbor the coal is unloaded from the boats and stored for future demand or loaded directly into cars for shipment to various points in Minnesota, North Dakota, South Dakota and Montana.

The storage capacity of all the docks at this port increased from 1,000,000 tons in 1900 to over 5,000,000 tons in 1910.

In 1906 there were two docks equipped for the use of electrical energy, both using direct current, one of them purchasing current from the local lighting company and the other owning and operating its own generating plant. In 1911, eleven of the twenty-one coal docks were equipped for the use of electrical energy, and nine of these are using alternating current directly on the hoisting apparatus, while another has installed a synchronous converter in order to supplement its existing direct-current generating equipment by the use of purchased power.

In 1909, twenty-six per cent of the coal received was handled by electrical energy, in 1910, forty per cent, and in 1911, it was estimated that sixty per cent of the total coal received would be handled by the use of electricity.

Before the introduction of electrical energy, the largest dock

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*One long ton = 1.016 metric tons.

had a storage capacity of 250,000 tons, whereas two of the newer docks have storage capacities of 1,000,000 tons each and another is projected of this same capacity but with provision for an ultimate storage of 2,000,000 tons.

The coal handling machinery as at present installed is divided into three types: bridge tramway, cable car, and man trolley.

Bridge Tramway. Figs. 1 and 2 give a general idea of the equipment on one of these docks.

The installation consists of moving bridges, locomotive cranes, box car loaders, and screening towers.

The boats are moored to the unloading side of the dock. In case the unscreened coal is to be shipped out immediately the bucket takes the coal from the boat and loads it into the cars at the opposite end of the dock. In case the coal is to be screened the bucket carries it to the rear end of the dock and dumps it into the screening towers. Moving buckets carry the screenings on to the screenings pile at the rear of the dock. The screened coal is loaded into cars by gravity. Coal for storage is dropped directly upon the storage pile.

Twenty-five-cycle, three-phase, 13,000-volt power is delivered to the terminals of a transformer house. Three 500-kw. three-phase transformers reduce the pressure to 440 volts for distribution about the dock. This distribution is accomplished in a novel manner. Posts about four ft. (1.2 m.) high, as shown in Fig. 2, are spaced at intervals along both ends of the dock. Three contacts about 15 in. (38 cm.) apart are placed vertically on these posts and the current is transferred to the moving machinery by means of shoes, which span two posts at a time. The cables for supplying current to the contacts are carried in troughs about one ft. (30 cm.) above the ground and protected by means of metal covers, which can be easily slipped off for the purpose of making repairs to the cables.

The bridges have an extreme length of 506 ft. (154.2 m.). The buckets are controlled from cabs at either end of the bridge. They operate by means of cables running over sheaves from the cabin on top of the bridge. One 225-h.p., three-phase, 440-volt wound-rotor motor drives the hoist for closing and hoisting the bucket. For moving the bridge two 75-h.p. motors are used.

The buckets are all of the clam-shell type and on three of the four bridges on this dock weigh seven tons and hold three tons of coal. The fourth bridge, installed in the spring of 1911, has a bucket weighing six tons and hoists four tons of coal. On this

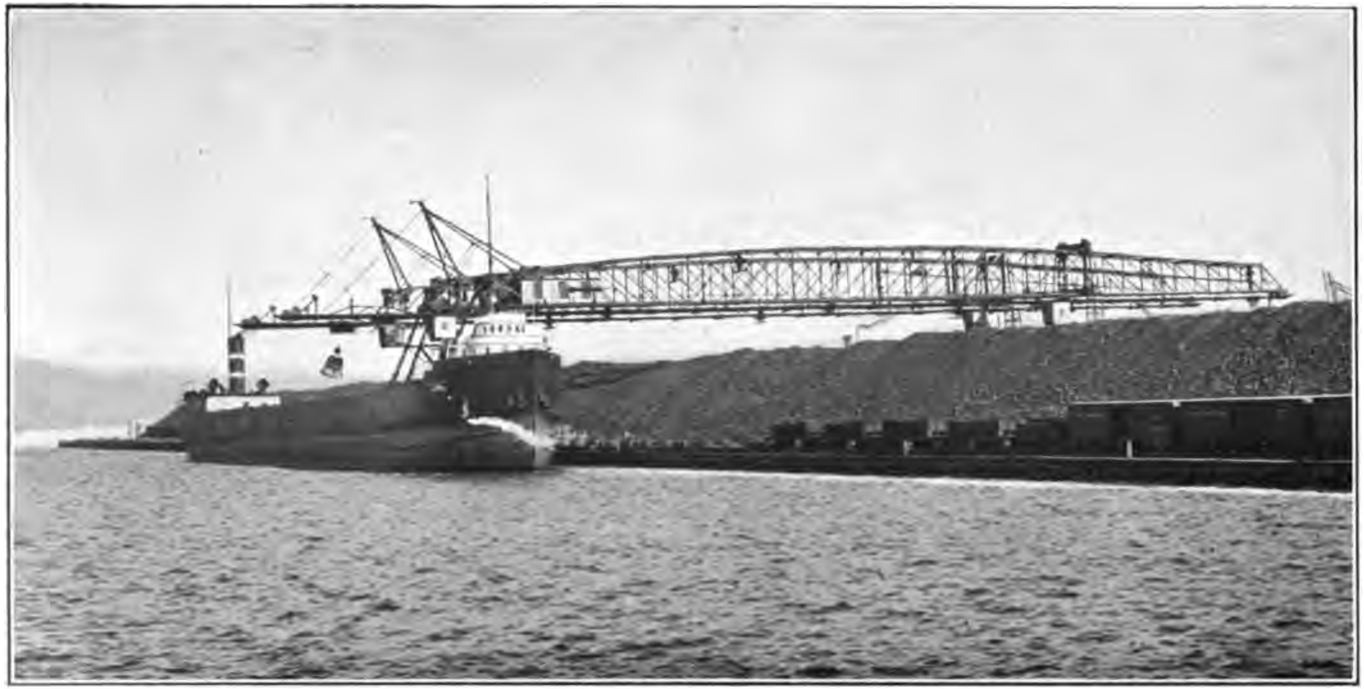

FIG. 1—BRIDGE TRAMWAY
Showing bridge unloading from boat

[RYERSON AND CRANE]

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FIG. 2—BRIDGE TRAMWAY [RYERSON AND CRANE]

Showing locomotive cranes, box-car loaders, screening towers and current posts latter bridge a 375-h.p. motor is used for hoisting and closing the bucket and one 225-h.p. motor for moving the bridge.

The older type of bridge has a hoisting speed of 300 ft. (91 m.) per minute and was guaranteed to make 60 trips and unload 180 tons of coal per hour, and has made 100 trips and unloaded 300 tons of coal in one hour.

The new bridge has a hoisting speed of 600 ft. (182 m.) per minute and has shown a capacity of 500 tons of coal per hour. This bridge has proved so successful that it is proposed to install similar apparatus on one of the other bridges this winter.

The control system on the bridges is alternating-current magnetic control and has given no trouble in three years of operation.

The braking is done by means of friction brakes released by solenoids. Hardwood shoes were at first used for this purpose. These caused considerable trouble from heating, and for the past two years asbestos shoes have been used with good results.

The locomotive cranes shown in Fig. 2 are equipped with 75-h.p. wound-rotor motors and are used for moving cars, hoisting coal from the screenings pile into cars, and loading coal from the side of the main pile into the loading hopper.

The box car loaders shown in Fig. 2 are equipped with 12-h.p. wound-rotor motors. These machines are used for moving cars and loading coal into box cars. Most of the cars loaded are of this type, the cars bringing wheat to Duluth and taking coal from Duluth. The loaders have an arm extending into the door of the car on the side opposite the receiving spout. The coal strikes the end of the arm and is thrown first to one end and then to the other by means of a reversible scoop operated from the cab of the loader by the operator.

All the electrically operated docks use the same type of box car loader.

The screening towers consist of hoppers into which the coal is dumped, and from which it falls into the car over screens. The screenings are emptied on to the screenings pile by means of moving buckets, operated by a 27-h.p. motor.

With three bridges in operation this dock has unloaded boats containing 10,500 tons of coal in 18 hours, and with four bridges in operation has unloaded a similar quantity in 13 hours.

No trouble of a serious nature has developed in three years' operation and the manufacturers of this equipment and the owners of the dock are satisfied with the results obtained. The dock was extended from 1200 to 2600 ft. (365 to 792 m.) in length this spring and some trouble was experienced due to excessive drop in voltage at the further end. This has been taken care of by moving one of the 500-kw. transformers to the lower end of the dock and running an underground 13,000-volt circuit to this point.

Cable Car. This installation, shown in Figs. 3 and 3A, consists of an elevated railway on which are mounted the hoisting towers and tracks for cars. The following apparatus is on the dock proper: screening pockets, unloading pockets, traveling bridge, conveyer belts, car loaders, and box car loaders.

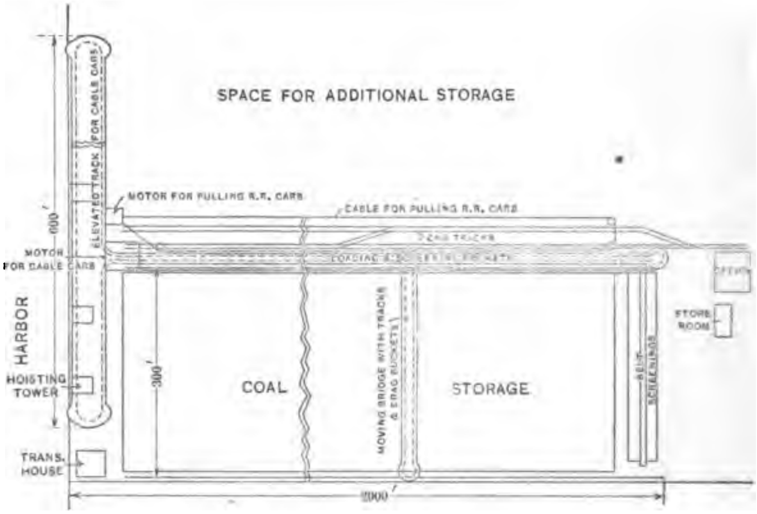

FIG. 3A—ARRANGEMENT OF DOCK FOR CABLE CAR EQUIPMENT.

Energy is delivered to this dock at 13,000 volts, three-phase, 25 cycles, and is reduced to 440 volts by means of three 500-kw., three-phase transformers. The energy is delivered to the hoisting towers and traveling bridge by means of trolley wires.

The boats at these docks are moored at the end of the dock. As shown in Fig. 3, there are three hoisting towers with swinging booms. These booms are swung over the boat, and buckets take the coal from the boat and empty it into a hopper. From the hopper it is loaded automatically into cars and these cars, operated by cables, empty the coal into loading pockets; or if the coal is to be stored, the cars are shunted on the traveling bridge and load directly onto the storage pile. In taking coal from the storage pile, shovel buckets are used and these empty the coal into the loading pockets.

The hoisting towers are equipped with clam-shell buckets, each weighing 6800 lb. (3084 kg.) and holding two tons of coal. There is a counterweight on these buckets weighing five tons. The motors are 200-h.p. wound-rotor, 440-volt, three-phase, 25-cycle. The hoisting speed is 600 ft. (182 m.) per min. The control is pneumatic and small air compressors are mounted on each tower. The braking is by friction and asbestos shoes are used, the levers from the brakes being controlled directly by the operator. These buckets average 144 round trips per hour and three towers have unloaded an 11,246-ton boat in 18 hours. This type of tower has usually been installed with steam-operated hoists and the manufacturers have claimed that the steam hoists were quicker. There are two other docks at this port using steam hoists of this type, but neither of them has been able to do as rapid work as the electrically operated hoists.

The cable cars are 11 ft. (3.3 m.) long, 5 ft. (1.5 m.) wide and 6 ft. (1.8 m.) high, and each holds four tons of coal. These cars pass under each hoisting tower and touch a lever which releases enough coal to fill the car one-third full. One 75-h.p. motor is used for operating the cables.

The screening and loading pockets are along the railroad tracks at one side of the dock and directly under the elevated cars. The loading pockets load directly into the cars by gravity. The screening pockets empty the coal into the cars after it has passed over the screens. The screenings fall on conveyer belts and are carried to the upper end of the dock and there emptied on to the screenings pile. One end of the moving bridge is connected to the elevated structure and the other rests on long legs, running on a track at the other side of the dock. The bridge is equipped with a loop track and in storing coal these tracks are connected to the elevated structure by switches and the bridge is moved along the dock as soon as one section is full. In loading coal from the dock two shovel buckets are used. These buckets hold two tons and empty the coal directly into the screening and loading pockets or into the cars, which in turn empty into the pockets. Wound-rotor motors of 150 h.p. capacity are used to operate these buckets.

The conveyer belts for the screenings are 24 in. (61 cm.) wide and are operated by 25-h.p. motors. They operate at 450 ft. (137 m.) per minute and carry 100 tons of coal per hour.

For setting cars a cable is run along the railroad tracks, and is operated by a 32-h.p. motor. The box-car loaders are similar to the ones described under " Bridge Tramway."

This type of equipment has been very satisfactory and the only trouble experienced has been with the air control freezing in winter, due to moisture collecting in the pipes, and some trouble with the motors on the hoisting towers.

The vibration on the towers is so great that it is hard to brace the end connections of the stator windings so that they do not rub against each other and wear the insulation. It has been necessary to rewind the motors twice, but it is thought that these are now braced securely enough to give no further trouble.

Man Trolley. The two types of equipment described above are adaptations of steam-operated rigs to the use of electricity. The man trolley equipment is an effort to devise something particularly fitted to the use of electric motors. It is, in its simplest form, a traveling crane on legs but using a bucket instead of a hook.

There are in use here at the present time two types. One uses a hoisting speed of 300 ft. (91 m.) per minute and a trolleying or racking speed of 1000 ft. (305 m.) per minute; the other uses a hoisting speed of 250 ft. (76 m.) per minute and a racking speed of 1200 ft. (365 m.) per minute. Fig. 4 shows the first type of dock.

The equipment consists of traveling bridges, screening hoppers, car pullers, and box-car loaders.

The energy is delivered at 13,000 volts, three-phase, 25 cycles, to the junction house, shown in Fig. 4, which contains oil switches, meters and lightning arresters. From this junction house the current is carried to 13,000-volt, three-phase catenary trolleys running the whole length of the dock. The transformers for reducing the pressure to 440 volts are located in the cabin at the top of each bridge. The 440-volt trolley for the box car loaders receives its energy from the transformers on the bridges. The machine shop and car pullers receive their 440-volt energy from a transformer located in the junction house. The boats are moored at the unloading side of the dock. The buckets empty the coal from the boat into the front hoppers if the coal is to go out unscreened and into the rear hoppers if it is to be screened. In case the coal is to be stored the buckets empty directly on the storage pile.

The buckets are of the clam-shell type, weighing eight tons

FIG. 3—CABLE CAR [RYERSON AND CRANE]
Showing hoisting towers and elevated railway

FIG. 4—MAN TROLLEY [RYERSON AND CRANE]
Showing junction house, screening hopper, 13,000-volt catenary and 440-volt trolley

FIG. 5—MAN TROLLEY [RYERSON AND CRANE]

Two views, showing terminal house and moving bridge with rear span detached, and attached, respectively: this span can be connected to either of the other bridges

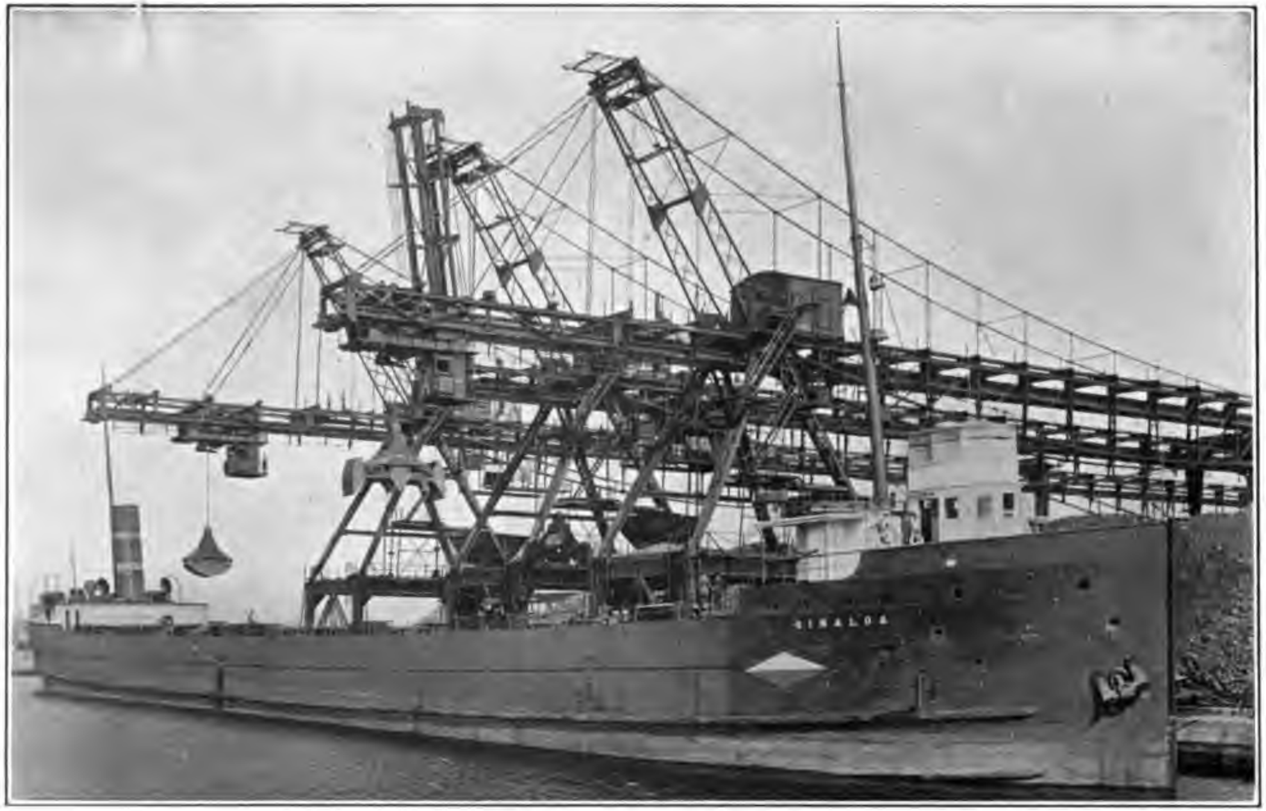

FIG. 6—MAN TROLLEY [RYERSON AND CRANE]

Showing bridge unloading from boats—center boom raised and not working

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FIG. 7—MAN TROLLEY [RYERSON AND CRANE]
Showing transformer house and method of distributing 440 volts to bridge

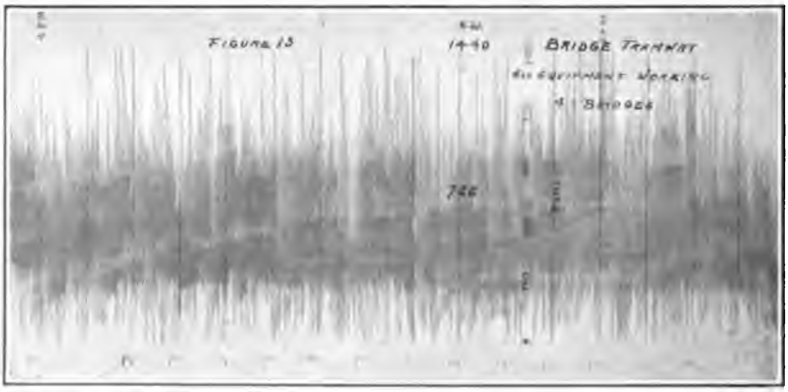

FIG. 13—BRIDGE TRAMWAY [RYERSON AND CRANE]
All bridges working

and carrying five tons of coal; the moving equipment, hoist, cab, air compressor, etc., weigh approximately fifty tons. Each hoist is equipped with two 150-h.p., three-phase, 440-volt, 25-cycle wound-rotor motors. Both motors are geared together and used for opening and closing bucket and for hoisting. For raising and lowering the boom one 30-h.p. motor is used. For moving the bridge along the dock, one 75-h.p. motor in front, and two 40-h.p. motors in back, are placed at the bottom of each leg. These bridges are guaranteed to make 50 round trips per hour from the hold of the boat to the storage pile. When " breaking down " a boat one of these bridges has made eighty trips and unloaded 400 tons of coal in one hour.

The control system is direct-current magnetic, actuated by air. The direct current is furnished by small motor-generator sets, and the air by small air compressors in each cab.

Both pneumatic and dynamic braking are used. In dynamic braking, direct current from the motor-generator sets is connected to the armatures of the hoist motors, with the secondaries short-circuited through resistance. This type of braking is satisfactory but requires the use of a considerable amount of additional energy.

The screening hoppers at the rear of the dock, shown in Fig. 4, empty the screenings on to the rear end of the storage pile, which is inconvenient, and some other method will probably be devised for disposing of the screenings.

The car pullers and box car loaders have been described before.

The second type of man trolley equipment is shown in Fig. 5. This type is equipped with clam-shell buckets weighing 7½ tons, while the total weight of moving equipment is 40 tons.

The energy is delivered to the transformer house, shown in Fig. 7, at 13,000 volts, three-phase, and is reduced to 440 volts by three 500-kw., single-phase transformers. The current is distributed to the bridges, as shown in Fig. 7, by three conductors running on the rear elevated stationary leg. Each hoist is equipped with one 225-h.p., three-phase, 25-cycle wound-rotor motor for closing and hoisting the bucket, and two 112-h.p. motors for racking.

The control is alternating-current magnetic, and has thus far operated with no trouble at all. The braking is friction, operated by foot levers.

The first type of man trolley equipment has been in use about two years, and while considerable trouble was experienced at first, the difficulties are being overcome and satisfactory results are now assured.

The second type of man trolley equipment has been in operation only about six months, so that definite conclusions as to its results cannot be drawn at this time.

SUMMARY OF COAL DOCKS

A comparison of the different types is shown in the accompanying table. While a larger number of cable-car bridges is in use, these bridges are of a smaller capacity and not as much coal is handled by them.

The kilowatt-hour figures per ton of coal are approximate only, as these are liable to variation from time to time, due to the way the coal is handled. At times a larger proportion is screened than at others; also in case of fire in a coal pile it is necessary to dig out all the coal near the affected area, which increases the kilowatt-hour consumption materially.

The friction type of brake is the most reliable and economical. Dynamic braking is more expensive to operate but is satisfactory with trained operators. The operators have also tried connecting the motors directly to the alternating-current line and using regenerative braking, but the drop of the bucket is too short to get satisfactory results. The alternating-current magnetic control gives the least trouble and is the simplest to operate and maintain.

COMPARATIVE TABLE OF THE DIFFERENT TYPES

Types of equipment	No. rigs in operation	Inst. peak per ton of coal	Peak occurs while	Kw-hr. per ton of coal	Braking	Control system	Distribution system	Yearly kw-hr.	Yearly l.f. on inst. peak
Cable-operated	3	119	Racking	1.09	Friction	A-C. magnetic	440 volts	980,000	8 %
Cable-operated	1	129	Hoisting						
Car system	9	90	Hoisting	1.38	Friction	A-C. pneumatic	440 volts	71,424	4½%
Man trolley No. 1	6	97	Hoisting	1.76	Pneumatic	D-C. pneumatic	13,000 volts	3,258,220	6 %
Man trolley No. 2	3	85	Racking	1.50	Friction	A-C. magnetic	440 volts	1,200,000	12 %

The load factor varies on the different types, partly on account of the different equipment and partly due to the methods of handling coal on the different docks.

The 440-volt distribution is the most satisfactory from an operating standpoint for both the coal dock and central station.

The copper for distribution is a little more expensive in the 440-volt distribution. The 13,000-volt distribution, while cheaper in first cost, has given trouble due to coal dust and smoke and steam from the locomotives collecting on insulators and in wet weather causing flash-overs.

The above figures are for handling bituminous coal. Anthracite coal is hoisted from boats by the same equipment and is carried into sheds by means of conveyer belts, etc., and so does not represent a radical departure from the usual conveyer systems.

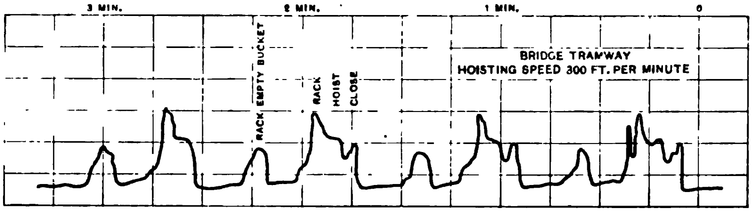

FIG. 8

The curves in Figs. 8, 9, 10, 11 and 12 were taken with a curve-drawing wattmeter speeded up to give two inches per minute. The highest point on these curves is liable to an error of from four to six per cent, due to overshooting on the part of the pen, but they are sufficiently accurate to give comparative cycles of operation for the different types of equipment.

In Figs. 8 and 12, the first type of cable-operated equipment and second type of man trolley equipment, the highest peak occurs while racking, while in the other types, as shown in Figs. 9, 10 and 11, the highest peak occurs while hoisting. The load factor is so low on the coal dock load that it is important to consider the peak, either when buying power or when generating it with the company's own plants. The most advantageous design from an economical and operating standpoint would be to have the hoisting and racking peaks the same.

In the above curves it will be noted that the extreme peaks are due to the acceleration of the motors and equipment, and that the actual peak, once the machinery is in motion, is 50 to 60 per cent of the above figures.

The curves in Figs. 13, 14, 15 and 16 show the daily operation of the different types of equipment, with whole docks in operation, and these are the curves on which the monthly bills are based.

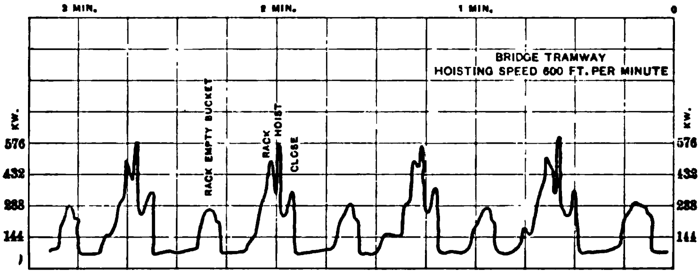

FIG. 9

Motors for use on the above work should therefore be designed for a low accelerating current and high starting torque and be especially well braced, as the excessive vibration on these towers is very severe on all the machinery.

It would be possible to design a dock with lower hoisting speeds, racking speeds, etc., which would handle the same

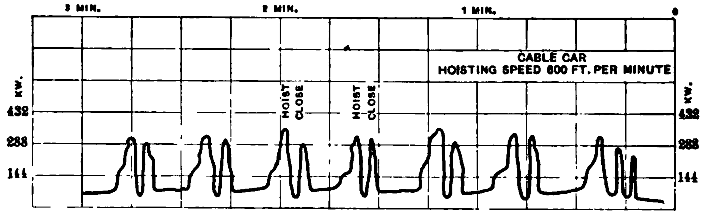

FIG. 10

amount of coal in a year and use current more economically, but it is necessary to unload large amounts of coal on short notice, as certain kinds of coal have a very limited movement to the lake ports, and at other times, due to congestion on account of storms, etc., a large number of boats are at this port awaiting dispatch.

During the winter months, when coal is shipped out only, the loading facilities are able to take care of from two to four times the number of cars the railroads can supply, and with smaller equipment for loading, such as is provided at the dock using cable-operated equipment, the kilowatt-hour consumption per ton of coal, and also the peak, is materially reduced.

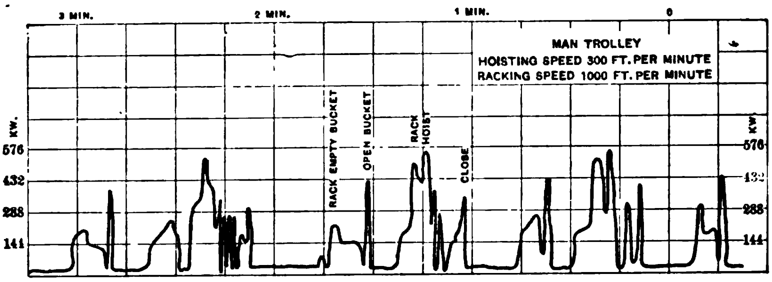

FIG. 11

One of the local coal companies operates two docks, one equipped with direct-current motors driven from its own plant, the other operated by alternating-current motors and purchased energy. The company expresses itself as seeing no difference in operating between the two methods.

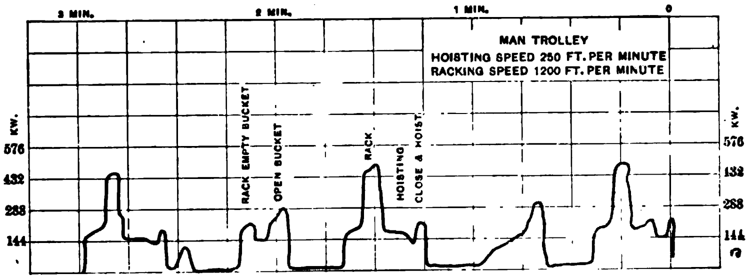

FIG. 12

In connection with its own direct-current plant it has a storage battery installed for taking care of the peaks. This year it became necessary to increase its power facilities and the following conditions were considered:

Synchronous converter using purchased energy.

Induction motor-generator set using purchased energy.

Additional steam-driven units.

Low-pressure turbines using exhaust steam from present engines.

Additional storage batteries.

The requirements were that the additional units must operate in parallel with the present steam-driven units.

The synchronous converter using purchased energy was finally decided upon, principally on account of its low first cost and the guarantee by the manufacturer of satisfactory operation. This machine was installed last summer and has worked satisfactorily and is taking care of the peaks and relieving the engines and storage batteries from the resultant shocks, so that a decrease in maintenance cost has already been noticed. The synchronous converter is compound-wound without commutating poles and is run with full series field. It is placed about 150 ft. (45 m.) from the main switchboard and each side is connected to the main bus by two 1,000,000-cir. mil cables. By using one or both cables it is possible to have the converter take a smaller or larger amount of the total load.

RATES

The rates charged for coal dock service are as follows: **$1.00** per month for each kilowatt of the minimum rating of the load, or " reservation charge."

$.011 per kilowatt-hour for all power used up to 70 kw-hr. for each kilowatt of rating of the load for the month for which charge is made.

$.005 for all additional power used, or " consumption charges."

The minimum rating of the load is the maximum rate at which power is used, as determined by curve-drawing meters, on the basis of the highest amount obtained from any of the following measurements:

The maximum instantaneous peak less 60 per cent discount.

The maximum one-minute peak less 50 per cent discount.

The maximum three-minute peak less 33⅓ per cent discount.

The maximum five-minute peak less no discount.

The minimum rating thus obtained is used until succeeded by a greater peak, and such increased minimum rating holds until a still greater peak is obtained, and so on during the life of the contract.

A curve-drawing wattmeter is installed at each dock for obtaining the peak and a watt-hour meter for obtaining the kilowatt-hour consumption.

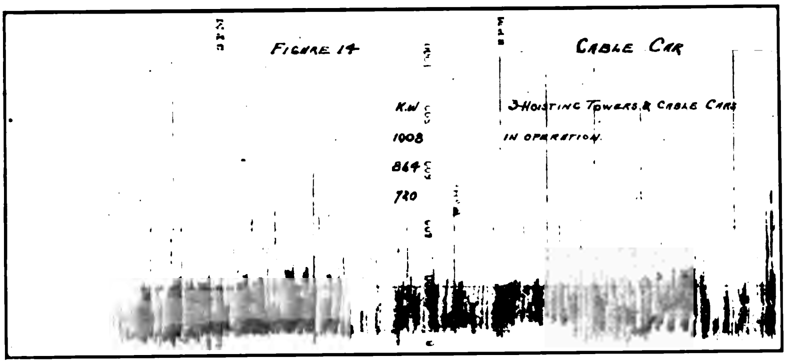

FIG. 14—CABLE CAR [RYERSON AND CRANE]
All bridges working

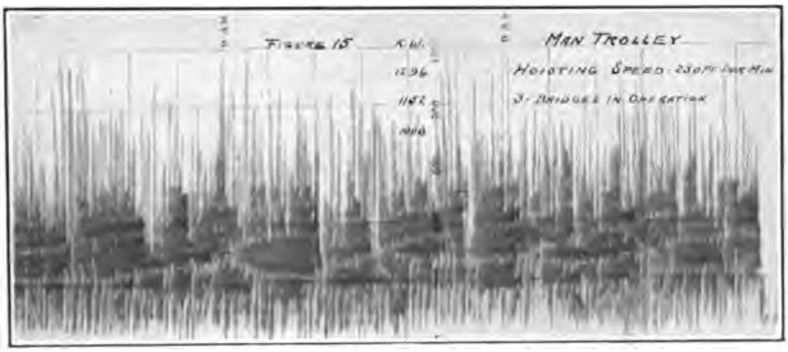

FIG. 15—MAN TROLLEY [RYERSON AND CRANE]
Two bridges, 250 ft. per min.

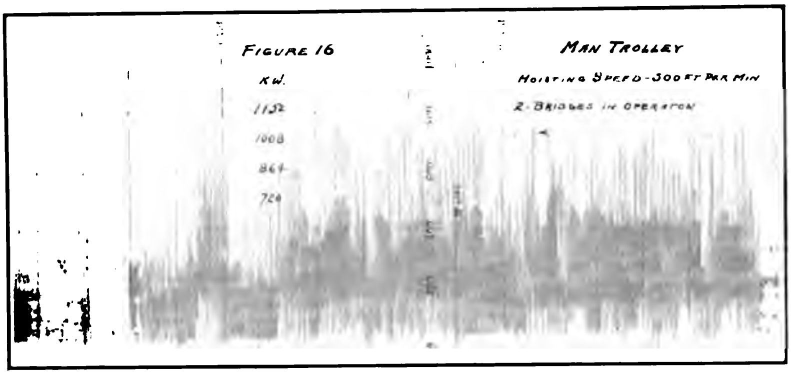

FIG. 16—MAN TROLLEY [RYERSON AND CRANE]
Three bridges, 300 ft. per min.

In coal dock service, the highest peak obtained is the maximum instantaneous peak, less 60 per cent discount, and this peak is used in determining the " reservation charge " for this class of service.

This method of charging gives a net kilowatt-hour rate varying according to the load factor, as shown in Fig. 17.

It would naturally be assumed that with a peak method of charge some form of flywheel equalizer would be installed at some of the docks. Owing to the sixty per cent discount from the maximum peak the installation of a flywheel does not offer sufficient saving to warrant the expenditure of a large sum of money for this purpose.

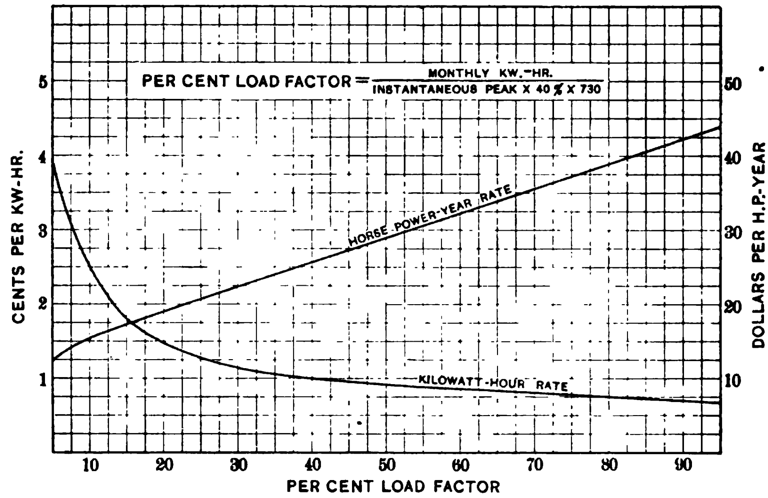

Fig. 17—Curve of Rates

Operation from Central Station

The power station is equipped with 7500-kw. generators driven by 13,000-h.p. turbines under a head of 375 ft. (114 m.). The turbines are fed by 7-ft. (2.1 m.) pipes, approximately 5000 ft. (1524 m.) long, and a standpipe is located at the lower end of the pipe line to each pipe. Oil pressure governors and mechanically operated relief valves are installed.

With all the coal docks in operation together with the other miscellaneous load, instantaneous load changes of 5000 kw. have been noted at the power station. With two units in operation no trouble is experienced with speed regulation, but with one unit only, the peaks cause hunting of the governor, and a resultant variation of frequency of 4 per cent either side of normal has been noted.

The coal docks using the 13,000-volt catenary trolley have occasioned some trouble to the underground cable system and substation oil switches, due to short circuits. The resultant surge affects the entire distributing system owing to the sluggishness of the dock switch.

For this reason all the coal docks with this type of distribution have been placed on the same feeder and it is expected that the installation of a different type of oil switch with either a time limit relay or reactance in the trolley connections at each dock will entirely do away with this trouble.

After three years of operation the use of alternating current for this class of service has proved commercially successful and it is safe to say that the majority of new installations at this point will be of this character.

DISCUSSION ON "NOTES ON THE USE OF ALTERNATING CURRENT IN UNLOADING COAL" (RYERSON AND CRANE), PITTSBURGH, PA., APRIL 27, 1912.

Wilfred Sykes: Having been more or less responsible for the first of the man trolley equipments installed at Duluth using alternating current, I would like to draw attention to a few points in the paper. The maximum rate of operation of the man trolley bridge has been given as 500 tons of coal per hour. I have some tests showing that in the case of one test, extending over a period of five hours, in which twelve minutes' delay was incurred, due to waiting for the boat, leaving a net period of 4 hr. 48 min., the bridge made 389 trips; about 40 per cent of these trips were to the first hopper for loading direct into the cars, and about sixty per cent of the trips went back 150 feet on the pile. That gave an average rate of operation of 74 trips per hour. The capacity of the bucket averaged a little more than five tons, so that the total amount of the coal handled was about 2050 tons. The maximum rate of operation over one hour was found to be 83 trips; the number was about evenly divided between trips to the hopper and trips to the pile.

In the paper it is stated that the dynamic braking of the alternating-current motors has proved satisfactory but is expensive. I would like to question that point. The use of dynamic braking was not contemplated at the start, was not really figured on, but the builders of the present bridge got into trouble through mechanical brakes and had to find some way of operating the equipment, the present equipment, which was finally arranged to be with alternating-current; but they did not know what they would run into, and they started in to put in a small motor-generator set for supplying direct-current to the hoist and the brake motors.

As a matter of observation I might say that the power consumption is very small, and you can easily see that, because the current through the stator, when braking, is about one and one-half the full-load alternating current of the motor. The voltage required is very low, because you only have to overcome the ohmic resistance of the stator windings. The motor-generator set for one of these bridges has a capacity of 140 amperes, direct current, at 40 volts, so you see it is quite a small affair, and the power consumption is somewhere in the neighborhood of thirty to forty watt-hr. in ten hours. As the current costs somewhat less on an average than one cent per kw-hr. the power cost is probably about fifty cents a day, twenty hours' operation. On similar bridges, in which they have mechanical brakes, using band brakes, originally starting off with wooden plugs, but since that was unsatisfactory, afterwards using asbestos lining, the cost varies from about $4 a day, in the worst case, which is a pretty bad case, down to $2 a day. It is hard to obtain reliable figures on the cost of maintenance of brakes of this kind, but those are the figures I have been given by the operators.

I want to draw attention to one feature of the man trolley bridge in the coal handling plant or ore handling plant, which should receive the closest attention of the designers, and that is that you must make the movements which the operator has to perform as few as possible, and the operator should be required to make only a very small expenditure of energy, because when a man is on a bridge for ten hours and is operating at high speed, he cannot put much energy into each operation, otherwise he is worn out and the quality of the attention which he can give his work is impaired. That was one of the reasons that led to the adoption of dynamic braking, because when a man is lowering a bucket and exercising the greatest care, where they have dynamic braking, he starts the bucket going down before the control is stopped, throws on one controller notch and lets the bucket go down 200 feet and about that time the bucket has passed through the hatch, and he cuts the controller off and puts the brake on. The introduction of the dynamic brake has facilitated operation and increased the capacity very materially.

Where you have a mechanical brake it is necessary for the operator to give more or less attention to that, whereas with the dynamic brake he does not think about the thing at all, but is chiefly concerned with centering the trolley over the hatchway. That is one of the points that makes a bridge with dynamic braking much easier to handle than a bridge with mechanical brakes.

On this first installation, and indeed on quite a number of installations, seven or eight of them, the controllers are operated by compressed air. It is necessary on these bridges to have compressed air for the clutches, anyhow; I think some have tried to use the electric clutches, but I do not believe they achieved any great success. The company which has built most of the bridges is very strongly of the opinion that it is necessary to have compressed air in order to obtain anything like reliable and quick operation, and the control as originally laid out in the majority of cases is with air operation. One of the reasons for using air operation is that this type of switch has been tried out in railway work, in which they are able to obtain great pressures at the point of contact; and any one who knows anything about brake control, knows that if you have given a pressure on the contact and a large force for opening the switch, you have increased the reliability very greatly, and that is one of the reasons that led to the use of air switches. Then, again, although alternating-current switches have been developed since that time, I believe it is a matter of opinion among operators which is the more reliable, and a great many operators prefer air-operated switches because of the fact that you have in the switch 200-lb. pressure on the contact and a force of about 150 lb. to open the switch, so you are sure of very reliable operation. In one of these plants there was some little trouble due to the moisture in the air freezing and blocking up the pipe, but with a proper arrangement of the air pipe so as to drain the moisture out of the system, I do not think there is any trouble now encountered in even the worst weather.

The paper has mentioned also the method of distribution, in one case using 13,000 volts, collecting the current at 13,000 volts, having a transformer on the bridge, and in another case having 440-volt distribution with stationary transformer. I think that is a good deal a matter of opinion. There is no question that with the 13,000 volts you can obtain a good deal better voltage regulation at the motors, and my experience has been that for work of this kind you want to get all the voltage you can at the motors, so that you can get as much torque as possible in the motors during acceleration, because if you do not do that the operators will complain.

There has been a little trouble due to the accumulation of soot on some of the insulators. I do not believe that amounts to much now, because in the first installations they put in too small insulators and did not appreciate the fact that locomotives would run beneath the line.

With the low-tension distribution, unless you use a great deal of copper and subdivide the lines, the voltage regulation is very poor when the bridge is working at points furthest away from the transformers.

As to the most desirable arrangement of these bridges, I believe one point has been overlooked. It is stated that the most desirable arrangement of the man trolley bridge would be to have the peaks during the racking and hoisting the same. That would be all right, if the peaks did not occur simultaneously, but, the way the bridges are operated, the hoist is stopped, sometimes it is slowed down going through the hatch, and accelerated again, but as soon as the control motion is thrown off the contacts overlap, and that is the worst test for the man trolley bridge—so I do not think that statement would stand. The most that could be said, I think, would be that that would be the most desirable arrangement when the contacts did not overlap. If that arrangement had been used on the existing bridges, the contacts would be very much higher than they are now.

In connection with the question of charging, I think I will enlighten Mr. Crane a little as to a conspiracy that was hatched up at one time, a method of beating the power company. If you put in a flywheel set and use the motor-generator set with a flywheel, and have an arrangement to introduce neutral resistance in the rotor of the motor for a brief interval, so that it will drop the load for two or three seconds, causing the graphic wattmeter to go back to zero, then you can all be charged on the one-minute peak. It is, however, possible that your input to the set will be practically the average load and, therefore, you can cut down your charge for reservation, and consequently your kw-hr. rate

There is one difficulty, it seems to me, which is a pretty serious difficulty, and that is, having as the basis of charge in such a system the necessity of depending upon some form of graphic recording wattmeters. We all know that alternating-current meters having very rapid fluctuations of load are likely either to lag too much or overshoot, and it is possible to have a good deal of trouble in that way, and to have an endless argument with the customer, especially if he finds out that the meter is overshooting. If he does not find out, it is all right. That is a point which has arisen and causes a great deal of bad feeling. In this particular case, where you are dealing with large operators, they can generally understand the justice of the system of charging, with a different basis of charge for different conditions. Generally, where you have small consumers who do not study these questions, you have a good deal of difficulty in explaining to them just why you should have different bases of charging.

The question as to whether the bridges shall be equipped only with alternating current or only with direct current, is one of importance where you are handling man trolley bridges. That is the bridge which I believe is the coming bridge, and one which will be used more and more every year. It is comparatively new, but the breakage of coal is a good deal less with that arrangement; and you can get very large capacity, and with the conditions in Superior, or in the Northwest, the breakage of coal is a very important item, especially when the dock may handle over a million tons a year. A very small reduction in the value of the fuel shows up as quite a large item at the end of the year.

In one of the installations most recently contracted for—not yet in operation—the man who is building the dock contracted for direct current, and that makes it necessary to have synchronous converters; in addition he has also planned for a fly-wheel equalizer, so as to have a direct-current motor on the bridge, the idea being that the direct-current motor is more reliable than the alternating-current motor and more accessible for repairs, and does not have to be repaired so often. That is a pretty serious matter. I do not believe that in the present state of alternating-current motor design these criticisms are justified, but the fact remains that such a dock is being installed and is to be put into operation this season, and if there are any present connected with the operating company I would like to hear their views on that question, because it is a matter of unusual importance and has been exploited a good deal by some of the power manufacturing people.

On the question of using equalizing machines, I quite agree with Mr. Crane. I do not believe it can be justified, on the rate of charging. If we take, for instance, the minute indicated peak loads, then we have a different condition, but I do not believe that with the present system of charging the use of the equalizing machine is justified.

C. T. Henderson: I would like to add a word or so to the remarks made by Mr. Sykes regarding the direct-current installation that is being made at the present time. It is a very pertinent fact that this direct-current installation is being put in for a company which now has a dock equipped with alternating-current motors. This would make it appear, at first glance, at least, that the dock people are not altogether satisfied with the alternating-current dock, and are looking for something better, either in the way of reduced cost of operation or convenience of operation, or perhaps both.

On the general subject of alternating current versus direct current for dock operation, it would appear to me that Mr. Sykes has not dwelt with sufficient emphasis on the fact that to get satisfactory operation out of alternating-current motors the voltage must be strictly maintained, because with alternating-current motors the torque that is available is in proportion to the square of voltage, and it does not take much drop of voltage to slow down the machine very appreciably, or, perhaps, on account of lack of starting torque, put it out of operation entirely. With the direct-current machines, reduced voltage does not cause any material reduction in torque, but simply a reduction in maximum speed of operation; that is, ultimate speed of movement attained.

On the question of dynamic braking, it does not appear to me that the people in the Northwest, or in fact the coal handling people in general, have been fully alive to the advantages of dynamic braking. There was a time when dynamic brake control was absolutely unknown; there was a time when no one ever thought of retarding the descending bucket in coal or ore handling machinery in any manner except by means of a mechanical lowering brake. Dynamic brake control was first installed, I believe, in connection with ore handling machinery, and it solved the problem of proper retardation so beautifully that I do not believe today that any ore handling machinery is being sold that is equipped with mechanical lowering brakes.

In comparing direct-current dynamic brake control with alternating-current dynamic brake control, it should be borne in mind that while, in the present state of the art, it is possible to get a certain amount of dynamic braking action with the alternating-current motors, they cannot entirely duplicate the performance of direct-current machines. For example, on the Duluth and Superior installations the alternating-current motors have their stators excited with direct current and are used to retard the descending load, but no attempt is being made to have the alternating-current motor slow the load down to practically a standstill before the holding brake is applied, whereas on the direct-current machines—the ore handling machines particularly—such procedure is almost the invariable practise. As a result, I can say that in one installation, which I have followed very closely for the last four or five years, the hoist brakes have so very little to do that the brake bands have not been renewed, and this, I believe, is a considerably better performance than has ever been obtained on alternating-current bridges, even with the dynamic braking.

On the question of overlapping peaks, it has been pointed out that with the man trolley rigs the highest peak is obtained at the moment when the operator starts the trolley, while he is still hoisting. On the direct-current machines which are being installed in the Duluth-Superior region this spring, I believe that series parallel control is being used on the trolleys, and provision is being made for preventing the operator from throwing his motors into parallel until the hoist operation has been completed—this with the idea of reducing the maximum demand that can be made by the bridge, and at the same time permitting the operator to get his trolley under way before the hoisting operation has been completed.

Returning to the question of alternating current versus direct current, and particularly to the last paragraph of the paper presented by Messrs. Ryerson and Crane, it might be interesting to a great many here to know that in addition to this one company that is putting in a direct-current dock at the present time, and which has an alternating-current dock that has been in operation, I believe, for more than two years past, there are two other installations being made in that same district and both are direct-current installations. All of this, I believe, goes to emphasize the fact that the coal people in that territory are just beginning to realize the advantages of dynamic braking as obtained on direct-current machines, just beginning to realize the advantages accruing from the use of series-wound motors for bridge service, and just beginning to fall more in line with ore-handling machinery practise.

Just one other point, in regard to current consumption. I was very much surprised to note in the comparative table of different types, given in the paper, that a minimum of 1.09 kw-hr. per ton and maximum of 1.76 kw-hr. per ton are indicated as being required for the handling of the coal in that territory. I had on several occasions been given figures that were considerably lower than those, but I cannot, of course, vouch for the accuracy of them. In Milwaukee, however, I have made a number of tests on coal docks, and in one installation, for example, that of the Milwaukee Coke and Gas Company, the average power required over a period of one month was 0.47 kw-hr. per ton, which figure includes the power required for the operation of the man trolley as well as the power required for the moving of the bridge.

It should be remembered in this connection that this particular bridge is of the type having a center pivot, and therefore does not require as much power to move it as the type of bridge which moves straight down the dock.

There is another installation in Milwaukee on which I made a series of tests, and in one case a cargo of coal—6000 tons—was unloaded with an average consumption of 0.25 kw-hr.

per ton. This figure does not include any energy for moving the bridges up and down the dock, because they were only moved a few feet at a time, only far enough to move them from one hatch in the boat to another. The largest handlers of coal in Milwaukee have given me a figure of 0.58 kw-hr. per ton as an average for their entire installation, which comprises some five or six docks, and in view of the figures I have submitted here it appears almost inconceivable that as much as 1.76 kw-hr. per ton should be required by the man trolley, type No. 1, as discussed in this paper.

E. Friedlaender: I would like to know if any fatal or minor accidents have occurred at these plants on account of using high-tension lines.

I would also like to ask how much of the load is actually lowered and if the empty bucket is heavy enough to overhaul hoisting machinery from a standstill and go down by its own weight. I understand coal handling docks are similar to ore docks, where the load is dropped by opening the bucket in its highest position. If this is the case, very little dynamic braking would be required, especially if the bucket is not too heavy.

Wilfred Sykes: There are one or two points raised by Mr. Henderson I would like to answer. In connection with dynamic braking on the alternating-current motor, the bucket is not stopped—the operators do not attempt to stop the bucket with the dynamic brake. They are very well satisfied if they can set the buckets running down, and forget them until they have gone to the hatch. The wear on the mechanical brakes when you do this is very small, and a set of linings will last several months with proper handling. You cannot get quite as good a record with this form of operation as you can with the direct-current operation, as mentioned by Mr. Henderson.

I did not mention that the brake is also used for the stopping of the trolley. The dynamic brake is not depended on entirely. As a matter of fact the brake is thrown on and the final stopping done with the mechanical braking, but the reduction of the wear on mechanical brakes by using direct-current on the stators is very great, and the life of the brake shoes has been increased ten times over what it was originally. We have also avoided a great many difficulties due to the iron dust, etc., getting into the windings.

Regarding the man trolley bridges I also notice the point raised by Mr. Henderson, as to the amount of kw-hr. required per ton—I do not believe that figure is intended to represent the power actually taken by the bridge. From the figures given, I think that must also include the power consumed by all the other motors required around such a coal dock. I have personally made many tests up there, and find, depending on what part of the dock you are delivering the coal, that the power required varies from about 0.4 to 0.6 kw-hr. per ton. That would show, however, a kw-hr. per ton for the actual input of the bridge. I believe this figure is borne out by the records kept over a considerable period by the operators.

The power required in the moving of the bridge, referred to by Mr. Henderson, is not very great anyhow—it is a very small percentage of the total power required for the operation of the equipment.

The point raised by Mr. Friedlaender about how much of the load is lowered is one which I thought would be clear, and would show why the dynamic brake is used. These buckets weigh anywhere from 15,000 to 18,000 lb., and with this man trolley, type No. 1, you cannot very well arrange for a counterweight. The loaded bucket weighs from about 27,000 to 37,000 lb., so that approximately 60 per cent of the total load lifted consists of empty buckets which have to be lowered every trip.

As far as accidents due to shock are concerned, I do not believe there are any. The only accidents I know of up there are due to men being caught between the trolley and some portion of the structure, or to the wrecking of the plant when one of the trolleys fell off the bridge altogether, but there was nobody killed.

R. R. Selleck: I was connected with the company that put in the docks shown in Figs. 5, 6 and 7, and was located at Duluth for about four months in that connection, and I became quite familiar with the handling of coal on these docks.

Now, there is one thing I would like to say at the outset, and that is that it is my belief that the alternating current is just a makeshift when it comes to handling coal or ore. It does not lend itself very rapidly to dynamic braking, and, as has been discussed here at some length, dynamic braking is absolutely necessary for quick operation; speed is what the men are after who own these docks. That is the first consideration. You will note by referring to the paper presented by Messrs. Ryerson and Crane that they give the weight of the trolley in one case as 50 tons and the weight of the trolley in another case as 40 tons. The 50-ton trolley is the one which had the dynamic brake. As a matter of fact, it came nearer being 60 tons, because I know the other one weighed 52 tons, and you will notice the appearance of the trolleys—there is certainly a difference of 10 tons in the weight of the two trolleys. That is of importance when it comes to the designing of a bridge structure, so that if you can reduce the moving load 10 tons, you will materially reduce the material in the bridge structure, and that is the first consideration, of more importance than the question of who is going to build the bridge.

It does not seem to be an economical plan to put on a trolley any more material than is necessary. By using dynamic braking, which requires a small motor-generator set, and in addition, an air compressor set, considerable weight is added. A man trolley does not have much spare room, either in the cab or on the superstructure. At best it is not a very commodious place, and anything that tends to cut down the amount of apparatus required on the trolley is of considerable importance, especially to the man who is to build it. So I do not think that alternating current is going to prove the big success in the handling of coal that was at first predicted. As a matter of fact, as has been already stated, several firms up there are going to direct-current.

A few words in regard to distribution. It has been stated that one of the docks takes energy at 13,000 volts, and puts it at that pressure directly on the bridge. The energy is taken off the catenary trolley system, transmitted across the bridge to the transformers, where it is stepped down to the voltage required on the motors.

Some emphasis has been laid on the relative cost of these two systems, *i.e.* 13,000 volts vs. 440 volts. As a matter of fact, I was connected with the making up of an estimate for the equipment that was to go in one of the docks at Duluth. This job was figured for 220 and 550 volts direct-current, also for 440 and 13,200 volts alternating-current, the idea being to arrive at these costs very carefully, and we found that 550-volt direct-current transmission was the cheapest. Then we got to 220 volts direct-current, then 440 volts alternating-current, and lastly 13,200 volts alternating-current, which is considerably higher than any of the others. That is due to the fact that you must put up a special trolley construction. That installation in this case was in the form of a catenary, and you must use quite an expensive insulation system, and in carrying the line across the bridge considerable care must be exercised to avoid grounds, so it figures out at the highest price of all, while your copper, in the case of the 440-volt system, where there were two parallel lines of 750,000-cir. mil cable, six of them, each running 1200 feet, runs into money. Notwithstanding that, we figured it was a cheaper installation than the 13,200 volts.

Mr. Sykes made mention of the fact that it was necessary to have air on one of these bridges to operate the clutch. He said that electrically operated clutches had been used, but did not give very good satisfaction. On this 440-volt bridge the clutches are operated by electricity, 48-in. clutches electrically operated, and to my knowledge the clutch has not given any trouble. It is working very satisfactorily; but, of course, you cannot throw a clutch in like one that is manually operated; you must have some auxiliary system to throw the clutch in—but as far as the operating of the clutch by air is concerned, it is not necessary to have that. It is not necessary to have an air equipment on the alternating-current bridge, that is the point; because it seems to me to be foolish to load up a man trolley with a whole power plant.

Now, one word in regard to regulation. It has been pointed out that the regulation on the 13,200-volt system was better than on the 440-volt system. I beg to differ on this point. We had three bridges on this one dock in operation at one time, and we had them at that time as far as we could get them away from the transformer house, about 1000 feet, and we were trying the regulation—that is what we did it for. We could not get any very satisfactory voltage readings, due to the " kick " of the voltmeter, and, of course, to the fluctuations that are instantaneous, but about the best we could do was to calculate that we got a drop of about 10 volts. If with three bridges in operation we got a drop of 10 volts, you would not notice any fluctuation in the pilot lamps on the trolley, so our voltage regulation was very good, and we did not have any trouble at all.

That answers the question raised in regard to the torque of alternating-current motors on a coal or ore bridge. If your distributing system is properly designed you will not get into any trouble with the torque falling off. We do know that it falls off as the square of the voltage, but if the distributing system is properly designed and sufficient cross-section of copper put in to take care of it, you will not get any appreciable drop of voltage and so there will be no difficulty there.

There was another question in regard to the lowering of the load. Of course, the breaking of the coal is an important item to the owner of the dock. When we first started to put coal on the dock they insisted on our lowering every load—that was when we were dropping about 30 feet from the bucket to the ground—but after we had a thin layer of coal on the dock they did not insist on our lowering the bucket, and after that the operator would run out the bucket and allow the coal to fall down. While some breakage might result, it was not considered serious. My experience has been that only the lowering of the bucket over the first layer is required, probably the first ten feet of coal on the dock.

Regarding the operation of these machines and the dynamic braking, as has been said, complications follow when you put dynamic braking on an alternating-current system; and anything that makes more complications necessarily decreases reliability. The intelligence of the men who are on these bridges is not of a very high order, and what the operators want, what the owners of the dock want, is speed—they want to get the boats dispatched as quickly as possible, and the men that are in them are a rough and ready sort of fellows (they do not seem to care whether they are killed or not) and their first and only thought is to rush the unloading of the cargo. All they are thinking of is to get the coal out of the boat, and they want something that is going to help them do this quickly; and for that reason I think that the dynamic brake, because it increases complications and decreases reliability, is something that is not very desirable for that class of work.

One speaker raised the question of safety appliances in these machines. We do not have very many safety appliances of any kind. As a matter of fact, I was in a trolley when it went off one of these bridges, and went down 65 feet. No serious harm was done.

R. E. Hellmund: One of the speakers said that it was not possible to reduce the speed to zero by dynamic braking. That statement is not correct. You can go down to three per cent of the speed any time if the requirements are such that you want to do it. The lowest speed you get is the slip of the motor at full load, which is usually about two to four per cent, and with such speed or any higher speed you can get all the torque you want.

Mr. Selleck seems to be rather opposed to alternating-current motors, especially on the ground that the equipment becomes rather heavy. He mentioned himself that a part of the weight was due to the compressed air outfit. That, of course, is not caused by alternating current—it might be used in one case or the other, either alternating current or direct current. I believe that the motor-generator set eventually can be reduced in size. Of course, as in anything else, a thing that you work out for the first time you work to safer limits, you allow a greater margin of safety, than you do after you have gained greater experience. I believe eventually the difference between the alternating-current and direct-current weight will be very small.

Wilfred Sykes: I will question one point raised by Mr. Selleck, and that is the regulation of the low-voltage distribution. He gave 10 volts. That corresponds to about 2.5 per cent. I have generally found that there is that drop in the transformer alone, without taking into consideration the lines.

Albert Kingsbury: It was my fortune, some nine or ten years ago, to have to make a report on the feasibility of using alternating-current motors in a coal handling plant. The report was made in reference to a large plant on Lake Superior, in which an attempt had previously been made to utilize alternating-current motors instead of steam engines. In discussing this question with the superintendent of the plant I found that he was very strongly opposed to the alternating-current motor. He told me that they had tried motors of the internal resistance type, not the wound-rotor type, and he found that the motors heated very badly, and that the brakes gave trouble. The heating of the motors and the brakes was so serious that the electric drive was abandoned and replaced by steam engines. Nevertheless, I reported that it was entirely feasible to operate the plant with induction motors, and I have now the somewhat doubtful satisfaction of being able to say " I told you so."

J. B. Crane: Most of the questions that have been asked seem to have been answered by succeeding speakers, but there are one or two things I would like to speak about. Mr. Sykes brought up the fact that dynamic braking was not as expensive as the mechanical braking. My figures on that point were secured from a company that had both systems in use, and they said that the mechanical braking was cheaper. Mr. Sykes says that it costs about $4 a month to replace the parts of the mechanical brake, while the superintendent of the dock where this system has been in use three years, and where they first started out using wooden blocks and changed to asbestos blocks, told me the asbestos blocks lasted from a year to a year and a half, and that is the only expense they have had in connection with replacement.

On this dock, which has been in use three years, and which was the first dock to install alternating-current motors at the head of the Lakes, there was no air whatever for operating clutches or anything else. Everything was controlled by alternating current, and there was not any direct current about the dock in any way. They were so very enthusiastic about it that when they put in the new bridge this last year they would not consider anything else, and wanted the bridge exactly the same, except that, because they wanted to handle more coal, they put in a larger bucket.

I want to say from personal observation of the fact, in going around to the different docks, that the man in charge of the electrical equipment of that particular dock can always be found around the office, whereas going to other docks the man in charge of the electrical equipment is always on the bridge attending to trouble.

In regard to the air-controlled system, we had this year fifty-six days in which the temperature did not go above zero. During that time they had considerable trouble with the water freezing in the pipes. We finally put a little alcohol in the pipes, and that seems to cut down the trouble from that source.

In regard to the method of charging and getting the peaks with the wattmeters, I would say that reliable and thorough wattmeters are not made for that kind of service. It is all right where you install it for an industry where the peaks are fairly steady, but on these instantaneous peaks it is hard to keep the wattmeter in condition, and there is trouble from overshooting.

We have made tests on several different makes of curve-drawing wattmeters and found that the overshooting varies from 20 to 60 per cent, depending on the extent of the peak, and also on the character of the load which is on when the peak starts. If you start from zero and go away across the scale, the overshooting will be 60 per cent. If you start from the middle of the scale and go across the overshooting will be only 20 per cent, and if you start a little higher it will be only 10 per cent. If you dampen your curve-drawing wattmeter to cut down the overshooting, the reading at the lower loads is wrong, and the errors on the lower loads will be anywhere from 20 to 40 per cent.

We have also made some tests with one of the printing attachments to integrate the peak, and we find that the integrated 5-minute peaks, when the peaks are in full operation, amount to practically the same as 40 per cent of the instantaneous peak, and it is possible we will adopt some other method in connection with this peak charge. When we first started in we had considerable trouble with the dock owners owing to this instantaneous peak, but that has practically been eliminated, because of the fact that we do not take the highest instantaneous peak each month, but take probably the fourth or fifth highest.

In regard to the discussion of alternating current versus direct current, and the fact that a new direct-current dock was going into operation at Duluth this year, I would say that while the owner of that dock has already an alternating-current dock in service, his adoption of the direct current was more on account of the fact that he is entirely opposed to alternating-current motors for any sort of use. He operates a coal mine and has had considerable experience with direct-current motors, and he says he would not have an alternating-current motor under any consideration. So the direct-current motor was adopted in that case simply on account of the fact that the owner is unalterably set against the alternating-current motor, rather than because the operators of the machinery consider the direct-current motor much superior for the operation of the dock.

The other direct-current apparatus going in is being installed on docks already equipped with direct current, so, of course, there is no reason why they should change to alternating current. As it happens, there are two alternating-current docks going into operation this year, and they will be as large as any other docks at that point.

The slowing down of the operation of the dynamic brake before the bucket reaches its lowest point is exactly the thing that the owners of the coal dock want to get away from. They want to run at the topmost speed until they get to the end and then want to stop immediately. That is the way they run the apparatus—they do not want to slow down and wait until they get to the end of the travel before stopping, and of course, that is why they are very hard on the motors.

The criticism has been made that the current consumption was high. The figures of current consumption were secured by taking the total kw-hr. consumption for the year and dividing that by the number of tons of coal that were sent out from that dock. That includes unloading the coal, and includes overhauling the coal—most of these docks have fires during the year, and when they have fires the men have to get down with the buckets and simply dig out the fire; that figure also includes the consumption of the car loaders and all the other apparatus about the dock.

The figures for the actual unloading of coal from the boat to the dock only, will vary, as Mr. Sykes said, from 0.35 to 0.6 kw-hr. per ton of coal, depending on how far the coal is taken back on the dock.

There has been but one serious accident on account of shock. One man was killed by getting on top of one of the hard coal sheds where the 13,000-volt line runs along on top of the shed, and he came in contact with the 13,000-volt wire and was killed.

In regard to taking coal up to the dock and lowering it to the dock, answering Mr. Friedlaender's question, the coal has to be lowered to avoid breakage; it cannot be dropped like ore. As soon as they get a pile started they keep unloading on the side of the pile, so that they do not have to lower the coal right down to the dock proper.

Regarding the breakage and loss in value of the coal, two of the docks at the present time have installed briquette plants, and they are making a success of briquetting the coal dust, which was formerly wasted, or for which they obtained only a very low price. A few years ago the coal dust was used for filling and practically thrown away, but gradually it came up in value from 20 cents a ton until now it sells at $1.90 a ton, and briquetted it sells for about $4 a ton.

There is always some breakage of coal due to the jaws closing on the coal in the hold of the boat, but that is one of the things that it seems impossible to guard against.

Considering the cost of installing 220- and 550-volt direct current as compared with 440- and 13,000-volt alternating current, I think the man who made the calculations must be mistaken. He gives the 13,000-volt system as the highest in cost. Several other companies that have made these calculations have found the 13,000-volt distribution very much cheaper.

The speed of operation is, of course, a very important point to the operators. In the car-equipped dock the buckets are only of 2.5 tons capacity, and the bucket makes 2.5 trips per minute. The operators have to work pretty hard all day long, and it is impossible to speed them up any more, because they simply cannot operate any faster. On the other hand, on the man-trolley docks, the operators only have to handle it about one and one-half trips per minute, and there is the chance of speeding them up if they can get apparatus that they can handle faster.

If Mr. Kingsbury could come to the head of the Lakes at the present time I am sure that he would agree that his predictions have been fulfilled in respect to alternating-current motors—that coal dock operation with them is certainly a success.

A paper presented at the 272d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 27, 1912.

DOES IT PAY THE AVERAGE COAL MINE TO PURCHASE CENTRAL STATION POWER?

BY GRAHAM BRIGHT

In the application of central station power to coal mines the successful operator of today is sometimes at a loss to know just what saving will be effected, for the following reasons: first, he believes that he is producing power at a fairly low cost, due to cheap fuel, simple apparatus and low cost of buildings; second, not knowing approximately his costs in detail, he is at first unable to see his saving, if any, as compared with a definite rate per kw-hr. for central station power; third, the use of central station energy often requires the purchasing of new apparatus, and the selling of the present generating apparatus under unfavorable conditions.

In regard to the first reason, the cost of fuel is, of course, low at the mine, but its value should be figured at the price that could be obtained for it if sold. The water question is often a serious one, and bad water in many cases occasions heavy repairs. The boilers, engines and generators as a rule are the simplest and cheapest obtainable, there being very little incentive for high economy at a mine power plant. Reliability is the first requisite, and with the class of skilled help obtainable about a mine, this reliability can be obtained only with the simplest kind of apparatus. The buildings are generally of the cheaper construction, and often have inadequate illumination, in which case the equipment does not receive the care it should.

In regard to the second reason, a certain rate per kw-hr. for power from a central station is not always an indication to the average operator as to what his total cost for power and his saving will be.

In regard to the third reason, in order to utilize central station energy it is usually necessary to purchase motors to replace the fan, hoist and compressor engines, and to purchase synchronous converters or motor-generator sets to replace the generators and engines driving them. The boilers, engines, pumps, old generators and piping must be sold, and it is rather difficult to get much more than scrap value for these, if they have been in use for several years. If the proper depreciation on the old apparatus has been charged off each year, the value carried on the books should not be very high. The difference between the value of the old apparatus and the salvage obtained for it must be charged off, or the entire value of the old apparatus must be charged off and the value of the new apparatus put on the books as the difference between the cost of the new apparatus and the salvage obtained for the old. To provide for this change new capital is required, and the members of the average board of directors must be assured of adequate returns before they will permit the expenditure of this new capital.

The purpose of this paper is to show a method of obtaining the cost of power at an average coal mine with its own power plant, and what the cost would be if central station energy were purchased at some definite rate per kw-hr. The values assumed are only approximate, as it is the method that is to be shown rather than actual values.

We will suppose that we are investigating a shaft mine, having the following list of power apparatus:

4 return tubular boilers, 18 ft. by 72 in. (549 by 183 cm.) Steam pressure, 90 lb. (40.8 kg.).
2 boiler feed pumps.
1 deep well pump.
1 feed water heater.
1 double balanced steam hoist. Max. h.p. of engine, 400.
1 ventilating fan. Horse power of engine, 50.
2 high-speed 150-h.p. engines for generators.
2 100-kw. 500-volt d-c. belted generators.
1 10-h.p. engine for machine shop.
1 10-h.p. " " screen.
1 25-h.p. " " elevator.
1 5-h.p. " " coal conveyer to boiler room.
2 steam pumps at bottom of shaft, 10 h.p. each.

The motors operated from the generators will have a combined capacity of about 500 h.p. The generators will be operated about twenty hours per day, the time depending upon the amount of electric pumping to be done. Some of the coal cutting is frequently done at night, which tends to improve the load factor on the generators, the lights and pump load being, as a rule, a small percentage of the capacity of one generator. The hoist will operate eight hours per day, with an occasional trip at night, or on non-working days. The fan will operate 24 hours per day. The tipple engines will work eight hours per day, and the steam pumps and coal conveyer will work intermittently.

The mine under consideration has an average output of 1100 tons* per day, and operates, on an average, 18 days per month all the year round. On days that the mine does not operate, one generator must be run to supply power for the pumps, lights and locomotives doing special work.

The operating force will consist of the following:

1 day engineer for the hoist.
1 " " " " electric plant.
1 night " " " " "
1 day fireman
1 day fireman's helper for wheeling ashes and helping around boiler room.
1 night fireman.

The wages of extra repairmen will be included in upkeep and repair charges.

The amount of coal used under the boilers will be about 500 tons per month, and this coal being slack, or a mixture of nut, pea and slack, its value will be about fifty cents per ton. In some plants it is necessary to use run-of-mine under the boilers, in which case the value is considerably higher.

To obtain the cost of power per kw-hr., it is of course necessary to first find out how many kilowatt-hours per day or per month are being produced. It is best to figure the costs on a monthly or yearly basis, in order to take into account the time lost when the mine is not operating. The cost per ton output for power will depend somewhat on the number of days per month or per year the mine operates, since a number of the items of expense go on just the same whether the mine operates or not. In this paper the costs will be figured on a monthly basis, taking the working days as the average per month for a year.

When obtaining the total kilowatt-hours the load factor should be determined at the same time, since the rate of charge

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*1 long ton = 1.01605 metric tons.

by the central station often depends upon the load factor. The load factor should be figured on the total five-minute or some other short time peak rather than on the capacity of existing machines, since the engines and generators installed are often very much larger than necessary, and their capacity is seldom reached by even momentary peaks.

The electrical kilowatt-hours, momentary and five-minute peak loads can easily be obtained by placing a watt-hour meter and graphic recording wattmeter or ammeter in the circuit of the generators for a 24-hour run, both for a working and a non-working day. The power developed by the steam engines driving fans, hoists, etc., is more difficult to obtain. If possible, these engines should be indicated, and from the cycle of operation, the horse power-hours or kilowatt-hours can be computed for a working and non-working day. Where it is not possible to use an indicator, the power taken by the fan engine may be calculated approximately from the size and speed of the engine, steam pressure, size and speed of fan, air pressure, and volume of air in cubic feet per minute. The power required by the hoist can be figured from the work being done and checked by the size and speed of the engine and the steam pressure. It is best to place the information in tabular form, so that ready comparison may be made. Table I shows the method of obtaining the total kilowatt-hours per month and the load factor.

TABLE I—CAPACITY, KW-HR. AND LOAD FACTORS.

Machines	Five-min. peak	Capacity in kw-hr. 24 hr.	Actual kw-hr. for 24 hr.	Capacity in kw-hr. 30 days.	Actual kw-hr. for 30 days.
Generators	150	4,800	800	144,000	19,200
Fan	40	960	680	28,800	18,000
Hoist	60	1,440	336	43,200	6,080
Elevator	20	480	160	14,400	2,880
Screen	5	120	40	3,600	720
Machine shop	5	120	40	3,600	1,200
Conveyer	1	24	8	720	160
Pumps	12	288	120	8,640	2,400
Total	293	8,232	2,184	246,960	50,640

Load factor for 24-hr. working day = 26.6 per cent.
" " " 30 days = 20.6 per cent.

In the first column are listed the various machines that are developing power. The second column gives the five-minute peak load for each machine. It will be noticed that for the generators this peak is less than the capacity, but this is almost universally the case in mine power plants. The fan engine runs at one speed during 10 hours of a working day, and at a speed requiring about one-half as much power for the remaining 14 hours, and for 24 hours of a non-working day.

The hoist has a peak load of about 300 kw. for five seconds, followed by a load of about 150 kw. for five seconds. The average time required for each trip will be about 52 seconds, but for intervals of several minutes, this time may be as low as 35 to 38 seconds. The five-minute peak is the average kilowatts for five minutes, with the hoist working at its maximum speed. At the average speed, this peak will be about 42 kw.

The third column shows the capacity in kilowatt-hours of each machine if it works 24 hours. The fourth column indicates the actual kilowatt-hours during a 24-hour working day. The ratio of column 4 to column 3 designates the load factor for a 24-hour working day. Column 5 shows the capacity in kilowatt-hours for 30 days, 24 hours per day. Column 6 shows the actual kilowatt-hours for 30 days. This column is made up of the figures of column 4 for 18 days, plus the kilowatt-hours for 12 non-working days. The ratio between the values of column 6 and column 5 gives the load factor for 30 days. The load factor of a mine plant depends largely on the amount of fan and pump load, and may vary from 13 to 40 per cent.

Table II shows the elements entering into the assumed installation, together with the possible savings in these elements when power is purchased.

The interest, depreciation, repairs and upkeep are indicated for each part of the power plant. No saving is figured on the engine building, since it will probably be used for the new motor-generator and switchboard. This apparatus should be so placed that the hoist engineer can look after its operation during the day. For the night shift a man can be obtained for about $60 per month.

In some cases where the generators are modern it may be advisable to retain these generators and purchase motors to drive them. As a rule, the average load on a mine generator is very much below its rated capacity. The peak loads are, however, rather high, so that the generators are really selected in regard to the peak rather than the average load. The type of load curve generally obtained on a mine generator is shown in some graphic charts (pages 11 and 12) in a paper in this volume of the TRANSACTIONS, entitled *Central Station Power in Coal Mines*, by W. A. Thomas. The older types of machines will not stand

TABLE II
Cost Based on One Month of 30 Days

Items Included in Cost.		Total present cost.	Amt. saved with purchased power.
Three engineers at $85.00		$255.00	$110.00
Two firemen at $75.00		150.00	150.00
One helper at $50.00		50.00	50.00
500 tons of coal at 50c per ton		250.00	250.00
Oil, waste and packing		50.00	40.00
Boilers:			
Cost, including stack	$4,000.00		
Feed pumps	200.00		
Setting and foundation	800.00		
Feed water heater	400.00		
	$5,400.00		
Interest at 5 per cent		22.50	22.50
Depreciation 7 per cent		31.50	31.50
Repairs and upkeep		50.00	50.00
Insurance		10.00	10.00
Boiler Building:			
Cost $2,000.00			
Interest at 5 per cent		8.35	8.35
Depreciation at 5 per cent		8.35	8.35
Upkeep and repairs		5.00	5.00
Engines:			
Cost Two generator engines	$3,000.00		
Hoist engine	1,500.00		
Fan engine	600.00		
Elevator engine	200.00		
Screen engine	150.00		
Conveyer engine	100.00		
Pumps	400.00		
Machine shop engine	150.00		
	$6,100.00		
Interest at 5 per cent		$25.40	$25.40
Depreciation at 6 per cent		30.50	30.50
Upkeep and repairs		30.00	30.00
Building:			
Cost $2,500.00			
Interest at 5 per cent		10.40	
Depreciation at 5 per cent		10.40	
Upkeep and repairs		5.00	
Piping:			
Cost $1,500.00.			
Interest at 5 per cent		6.25	6.25
Depreciation at 7 per cent		8.75	8.75
Upkeep and repairs		15.00	15.00
Generator, switchboard and wiring:			
Cost $2,640.00			
Interest at 5 per cent		$11.00	$11.00
Depreciation at 5 per cent		11.00	11.00
Upkeep and repairs		15.00	15.00
Superintendence		25.00	
Taxes at 1 per cent. of valuation (assessment 90 per cent.)		15.00	7.50
Liability insurance at $1.33 per $100.00		6.05	4.15
Overhead		50.00	
Total cost		$1,165.45	$900.25
Fixed charges		284.40	
Operating expenses		881.05	

peak loads much beyond their rated capacity, and even if they would, the engines are seldom in condition to take care of these loads. This characteristic of the engines is really a blessing in disguise for the generators. A modern commutating-pole generator driven by an induction or synchronous motor can be purchased to give 100 per cent overload for short periods with little or no drop in speed and with good commutation. The retaining of the old generator would require a foundation for the motor, a belt, a coupling and probably an extension to the building. The total cost will about equal the cost of a new motor-generator set, while the latter will be a much more satisfactory combination. Synchronous converters are also used instead of motor-generator sets, depending upon the local conditions.

The item "superintendence" includes that part of the salaries of the master mechanic and superintendent chargeable to the production of power at the mine in question.

TABLE III

COST OF NEW EQUIPMENT

1	150-kw. motor-generator set	$2,800.00
1	switchboard	150.00
1	75-h.p. induction motor with starter for fan	950.00
1	250-h.p. " " " control " hoist	2,500.00
1	30-h.p. " " " starter " elevator	400.00
1	10-h.p. " " " " " machine shop	170.00
1	10-h.p. " " " " " screen	170.00
2	10-h.p. motor-driven pumps	650.00
Installing, including foundation, wiring and buildings		1,000.00
	Total cost	8,790.00

Taxes are figured at 1 per cent per year, on an assessment of 90 per cent of the valuation.

Liability insurance is figured on the pay roll.

"Overhead" includes that part of the salary of the officers and clerks of the company and of the office expenses chargeable to the production of power, and should be the same proportion of the total overhead that the cost of power is to the total cost of production.

The total cost per month is $1,165.45, of which $284.40 is a fixed charge and $881.05 the operating expense. The saving per month with purchased power is $900.25. Since the total of kilowatt-hours per month is 50,640, the total cost of power per kilowatt-hour is $0.023. The saving with purchased power will be $0.0178 per kw-hr. The difference between these values, or $0.0052, is the common cost per kilowatt-hour, which will exist in either case.

In Table III is given a list and cost of the new equipment which must be purchased in order to utilize central station energy. Motors are provided to replace the present steam engines. All motors are alternating-current motors, and can be operated at any time, independently of the supply of direct current. In some cases it may be preferable to supply a direct-current motor for the hoist, in which event a larger motor-generator is required. This increase may be in the form of a larger generator or of two generators driven by one large motor. One of the generators would be used for the direct-current supply for the mine and the other, with special control, for the hoist. If possible, the old hoist should be sold complete and an entire new electric hoist installed. In the present case, an alternating-current motor will be substituted for the steam engine at the hoist. An adjustable speed alternating-current motor will be supplied for the fan. In many cases air compressors are used to supply air for punchers and pumps. It would be advisable to do away with air compressors entirely, and install electric cutters and motor-driven pumps, as the efficiency of the air system with its usual leaks is very low. However, in gaseous mines, it is sometimes considered dangerous to operate electrical apparatus, in which case a motor-driven compressor should be furnished.

TABLE IV

SALVAGE ON OLD EQUIPMENT

4 boilers with stacks		$400.00
2 feed pumps and water heater		90.00
2 150-h.p. generator engines		600.00
2 100-kw. generators with belts and switchboard		600.00
Engine part of hoist		50.00
1 elevator engine		50.00
1 fan engine		75.00
1 screen engine		25.00
1 machine shop engine		25.00
1 conveyer and engine		30.00
2 steam pumps		50.00
Piping		50.00
Total salvage		$2,045.00
Total net cost		6,745.00
Interest at 5 per cent for 1 month	$28.00	
Depreciation at 5 per cent for 1 month	28.00	
Upkeep and repairs	15.00	
Total	$71.00	
Operating and fixed charges per kw-hr. for new equipment		$0.0014

One thousand dollars has been allowed in Table III for the installation of the new apparatus. This should be ample to provide for foundations, alterations in building, wiring and mechanical application. The total cost is $8,790.

In Table IV is shown the probable salvage that could be obtained for the old apparatus. These estimates should be kept rather low, since it is sometimes difficult to get good prices for old apparatus. The total salvage amounts to $2,045. The net cost of new equipment will, therefore, be $6,745. The interest, depreciation, upkeep and repairs on the new equipment will amount to $71.00 per month. This is at the rate of $0.0014 per kw-hr.

In Table V some specific costs and savings are given. The total cost of power per kilowatt-hour, saving per kilowatt-hour with purchased power, and the common cost in either case, as before mentioned, are first shown. If the common cost is added to the cost per kilowatt-hour with new equipment, we have $0.0066 as the total cost per kilowatt-hour with purchased power, exclusive of the charge of the central station. If this value of $0.0066 is subtracted from the total cost per kilowatt-hour of $0.023, $0.0164 is obtained as the central station charge which would make the total cost of power the same as at present. In other words, if the central station rate were $0.0164 per kw-hr. the total cost of power would be the same as at present. Any rate below $0.0164 will, therefore, represent a clear saving. At a rate of $0.0125 per kw-hr., the saving would be $0.0039 per kw-hr., or $2,375 per year, which is a saving of 35.3 per cent. over all charges on the new investment. At this rate, the change would pay for itself in less than three years. At a rate of $0.01 per kw-hr., the saving would be $3,890, or 57.8 per cent. At this rate, the change would pay for itself in less than two years.

TABLE V—COSTS

Total cost per kw-hr. for power	$0.023
Saving per kw-hr. if power is purchased	0.0178
Common cost, in either case, per kw-hr	0.0052
Net operating and fixed charges per kw-hr. for new equipment	0.0014
Total cost per kw-hr. with purchased power, exclusive of central station charge	0.0066
Charge per kw-hr. by central station which would balance present cost.	0.0164
Saving per year at central station rate of $0.0125 per kw-hr	2,375.00
Percentage profit on net investment of $6,745.00	35.3 per cent.
Saving per year at central station rate of $0.01 per kw-hr	3,890.00
Percentage profit on net investment	57.8 per cent.
Present cost per kw. capacity (5-minute peak) per year for fixed charges	$11.65
Present cost per kw-hr. for operating expenses	0.0174
Total cost per kw-hr. with purchased power at $0.0125 per kw-hr.	0.0191
" " " " " " " " $0.01 " "	0.0166

A coal operator will readily understand that in his isolated plant he will have certain fixed charges which will be practically the same whether his plant operates or not. His power cost can be divided into fixed charges and operating costs. A central station supplying power for his mine will also have a certain part of its total cost as fixed charges. In many cases the fixed charges of the central station will be less than the operator's own fixed charges. The logical basis upon which to charge for central station power would therefore be a certain fixed charge per kilowatt capacity of substation or kilowatt demand, plus a rate per kilowatt-hour which will be equivalent to the operating expense. In the present case, if the fixed charge were made $12.00 per year per kilowatt demand on a five-minute peak basis, the charge per kilowatt-hour would be $0.0067 to make the total cost equivalent to $0.0125 per kw-hr. With the fixed charge system the total cost per kilowatt-hour decreases with the amount of power used. This is an incentive for the operator to extend the use of power as much as possible.

TABLE VI

GENERAL DATA

Average working days per month	18
Electrical kilowatt-hours per working day	800
" " " " non-working day	400
Total steam and electric kilowatt-hours per working day	2,184
" " " " " " " non-working day	944
Maximum electrical kilowatt demand, momentary peak	180
" " " " five-minute "	150
Maximum total steam and electric kilowatt demand, momentary peak.	450
" " " " " " " five-minute "	293
Capacity of generators	200
Total kilowatt-hours per month	50,640
Kilowatt-hours per ton output, based on 19,800 tons per month	2.56
Present total cost of power per kilowatt-hour	0.0234
Present cost per ton output for power	0.0588
Cost per ton output for power with central station energy at $0.0125 per kilowatt-hour	0.0489
Cost per ton output for power with central station energy at $0.01 per kilowatt-hour	0.0425

There are certain advantages that central station power has over isolated plants that cannot be measured in dollars and cents, and in most cases, even when the fixed charge is the same as the operator would have in his own plant and the charge per kilowatt-hour is equal to his own operating expense, it would still be greatly to his advantage to purchase central station power.

In Table VI is given some general information in regard to the results of the tests and investigation that should be made at a mine. The momentary and five-minute electrical peaks are obtained from the graphic records. These graphic records are very interesting and show clearly the extremely fluctuating nature of the load, as well as the low average load. The maximum momentary electrical load is often less than the continuous capacity of the generators. A modern commutating-pole generator of 100-kw. capacity would easily take care of the load where two 100-kw. old type machines are used at present. A 150-kw. generator has been figured on to allow for the additional load of the pumps when changed to electric, and also to provide for future extensions. The information given in Table VI will serve as a guide for the central station in determining the capacity of its lines, transformers, meters, switches, etc. The power required is 2.56 kw-hr. per ton mined. Since the cost per kilowatt-hour is $0.0234, the present total cost of power per ton mined will be $0.0588.

Summarizing the above information, the following reasons are given to prove the advisability of a mine's purchasing central station energy rather than generating its own power.

1. Lower cost of operation.

2. Worry and care of power plant removed. The legitimate business of a coal operator is to mine and ship coal, and he should not try to carry on another business of so different a nature, at the same time. The efficiency of his plant will be greatly increased if he can spend his entire time in looking after the mining and shipping of the coal.

3. Reliability, which means greater production.

4. Much less expense involved in shutting down mine.

5. Capital needed for new power plant can be used for new development.

6. Increased output and additional power can be obtained quickly with small increase in capital.

7. Increase of production on account of increase of efficiency, due to ample power at all times.

8. No change in speed of fan and pumps due to steam pressure falling occasionally.

About the only disadvantage is that additional capital is often required with which to purchase new apparatus, but when the large returns in the shape of decreased operating expenses are shown, this capital is not difficult to obtain.

DISCUSSION ON "DOES IT PAY THE AVERAGE COAL MINE TO PURCHASE CENTRAL STATION POWER?" (BRIGHT), PITTSBURGH, PA., APRIL 27, 1912.

E. D. Dreyfus: We are indebted to Mr. Bright for having added another interesting chapter on the subject of electric drive and the use of central station power, and in taking the opportunity of opening the discussion I wish to make note of some important facts which should be kept in mind in connection with the quotation of rates for power purposes. Mr. Bright has been obliged to confine his comparisons to specific cases only and personally I feel that his deductions are very instructive and valuable.

But in regard to the cost of power generally, a note of warning should be sounded, as a wide variation is liable to be encountered, depending upon local conditions. To exhibit the extent of possible fluctuations in cost, I have assumed a number of changes in conditions at random and obtained the following variations:

(1) With the size of the unit sextupled, the cost per kw-hr. would be reduced from 2.05 cents per kw-hr. to 1⅛ cents per kw-hr. total, all other conditions remaining the same.

(2) Now, with the plant quadrupled by adding, say three additional units of the same capacity, the cost would be lowered from 2.05 cents to only 1⅓ cent per kw-hr. total.

(3) If the load factor were improved from 25 per cent to 75 per cent, (high percentage taken for the purpose of illustration), the cost would be decreased from 2.05 cents to somewhat less than a cent per kw-hr.

(4) On the other hand, reducing the size one-half, the cost would rise from 2.05 cents to 2¾ cents.

The basic conditions are a 300-kw. condensing steam unit, $1 coal and average operating economies.

The above facts apply with the same force to the independent plant and are likely to be more serious in the case of light load factor.

George R. Wood: There is one point which has not been brought out clearly, which is that the saving in cost of power, though important, is less than the saving on other items in the cost of coal per ton. I think Mr. Bright's figures show a saving in power cost of 1½ cents per ton of coal produced. My experience has shown savings as high as five times this amount due to these other items, chiefly in labor and repairs.

The items on the cost sheet affected by higher and more uniform voltage underground are: (A) overhead, including interest and depreciation on investment; (B) labor, including operating and repair men; (C) supplies. (A) is reduced on account of increased production with the same equipment, which in some cases amounts to 30 or 40 per cent; (B) is less for the same reason, and also because repairs and upkeep are substantially reduced; (C) is also reduced on account of fewer burn-outs and increased efficiency of apparatus.

As a concrete example I might quote a large mining concern, which four years ago was operating 10 power plants, averaging 400 kw. each, at 550 volts direct current. The power distribution, over a very large area, was very good, better than the average mining plant. About 40 locomotive armatures per month were repaired in the shop. A central power plant of 2500 kw. was installed, with seven substations located near the centers of power consumption. The saving in power cost was almost four cents per ton, or about one cent per kw-hr. produced, while the total saving was nearly ten cents per ton, or in other words, the saving incidental to better underground voltage was approximately 150 per cent of that due to saving in cost of power alone. There are now not more than four locomotive armatures shopped per month, out of 168 in service.

H. M. Gassman: I am particularly interested in this paper, as I had occasion to solve the same problem, occupying the dual position of being interested in central power generation and distribution as well as looking after a large number of isolated stations and substations in connection with coal mines. As far as the central station is concerned the load is desirable, being largely a day load, and the fluctuating nature of the load of one station is not objectionable, provided a sufficient number of stations can be secured.

I wish, however, to take exception to some of the items in the summary; first, " lower cost of operation." This I assume refers to the cost per kw-hr. delivered at the switchboard; if not, then there is some question about it, as the isolated station will have to pay for the loss in transformation and also ultimately for the transmission loss. Second, " worry and care of power plant removed." I do not think that it is of great importance, unless the power companies contract to deliver the power to the switchboard. Then, in that case, we still have to contend with an organization to take care of the power consuming apparatus. In item 7 Mr. Bright says: " Increase of production on account of increase of efficiency, due to ample power at all times." The power available is limited by the transforming capacity of the apparatus installed.

There is one point I wish to call attention to, in the tabulated data, where the mention is made of " 500 tons of coal at 50 cents per ton." In figuring the saving, you can only count on saving the profit on the coal which if not burned under the boilers might be disposed of at a profit. This will make a slight difference in the figures, but in general it does not affect the discussion.

In addition I would like to point out some of the disadvantages of the central station power supply. One of the factors that has been omitted in this discussion is that of the transmission line. This is objectionable not only because it introduces a new factor of line loss and regulation that is not present in the usual isolated station, but because of the danger of interruptions of the service seriously crippling the output. We have to consider more than the actual cost of the power; *viz.*, the loss of profits, that is the loss of product. As an illustration of this I will refer to Table V. At a rate of saving of $0.0125 per kw-hr. the saving is estimated to be $2,375.00 per year. Let us figure that back and find what that is equivalent to in tons output. Assuming say 30 cents profit on a ton, this represents the profit on 8000 tons, or at the rate of production suggested by the author, this would be equivalent to seven days' output. If power is brought from a distance, the interruptions of power at the substation might very easily amount to seven days in the aggregate per annum, if delays and disorganization due to short interruptions are considered. The self-contained generating station is the only thing a steel man will consider. In fact, wherever any important output is at stake, the question of control of the power supply will have to be carefully weighed.

Considering all the advantages and disadvantages, I would favor, in the case of old mines, installing supplementary power, purchasing it either from central stations or from other sources, and retaining the old equipment, largely for the reason that the salvage obtained from the old equipment is very small and not sufficient to warrant disposing of it in view of its value as a spare in case of some serious interruption of the purchased power. It also would be an advantage in case of emergency, such as increased demands for power during the wet season. I consider the advantage of supplementing the old equipment as far superior to any attempt to abandon it. As far as a new mine is concerned, it is a very much larger question to solve, and it would be foolish to make any general statements as to whether it would be better to purchase central station power or establish generating stations for any particular mine, without full knowledge of local conditions.

E. T. Penrose: In regard to the central station purchasing power, or the centralization of power, I have been on both sides, purchasing and selling, and I have installed power in about sixty mines. In the first place, consider the matter of the transmission line. If we refer to Dr. Steinmetz's paper,* *Some Problems of High-Voltage Transmissions*, his statement is that there should be no interruption, and there is no reason for any interruptions except from faulty construction. I have found that all interruptions were caused by faulty construction.

As to the saving to the mine, particularly, as mentioned in this paper, to a group of mines, it is very questionable whether the purchasing of power from a lighting company, or what is known as the central station, would necessarily be a saving over the installation of a central plant to supply the various mines in the district; the mine company in that case taking the loss of transmission, upkeep, etc. In my opinion, ten or twelve mines in a given territory would be almost, if not quite, of sufficient size to

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*See page 169 of this volume.

compete with a central station power plant, as the cost per kw-hr. is absolutely dependent on the load factor, and it is a question if the centralization of the power plant for the mines would not give as high or a higher load factor than that obtained by the central station with the present methods of making rates.

The great advantage I have had in installing central power in the mines has been due to the fact that the small mines do not have the proper engineering ability, and therefore do not run their equipment in the best possible way. Burning out of armatures, which was mentioned, was overcome, not from the fact that they had central station power, but from the fact that substations were installed and high voltage furnished to the mines. Therefore, it was a mechanical engineering proposition, rather than the saving in the purchasing of electric power. However, for the last ten years, I have been strongly recommending the purchase by the coal mines of central station power, when a rate can be obtained from the central station which would be a saving. This rate in many central stations in the coal mining districts is hard to obtain, owing to the fact that it must of necessity be much lower than the average cost of current as produced by the central station. However, the central stations have their maximum load, varying from two to four hours a night, the four hours being in the winter time. During that period they would have their highest load, and owing to the larger development in recent years of power business in the central stations they have got so that some of them run up to 50 per cent load factor. The coal companies could have an average load that would be very close to the maximum for eight hours of the twenty-four during the working period, which would, of course, bring their load factor to about 30 per cent, so that in many cases the coal mine will have a better load factor than the central station.

However, it is the business of the central station to sell power and it is hardly the province of coal operators to do this. The main thing which is against the centralization of the coal properties plant is usually the lack of water for condensing and for boiler purposes. To show the inefficiency of the average coal plant, they will use anywhere from 15 to 35 lb. of coal per kw-hr. That may sound a little high, but it is so. The electric light plant should, with a given load factor, run with a large plant as low as three to four lb. of coal per kw-hr., and possibly lower than that with good coal.

Therefore it is a case of whether the coal companies shall get together and centralize their own power business, or whether they shall allow the central station to centralize their power. I am in favor of letting the power company take charge of this centralization, provided they would give the coal company proper rates.

H. M. Gassman: I think some of the previous speakers misunderstood my remarks. I do not wish to appear to be unfavorable to the central station supply for coal mines, but think that the advantages and disadvantages should be presented impartially, and conditions in other than the Pittsburgh district be considered.

My statement that the interruptions of supply from central station should be considered in making a decision is based upon experience in a locality where conditions are not so favorable as in the vicinity of Pittsburgh. It is not my intention to call particular attention to the interruptions resulting from trouble in the central power station, but rather to the interruptions of the service due to line troubles and voltage disturbances which would result in shutting down synchronous transforming apparatus. The service supplied through country that is less developed and more exposed to lightning troubles than the Pittsburgh district cannot be as good as where the conditions are more favorable. This is particularly true on systems with a single station and where the lines do not form a part of a large network.

Furthermore, my reference to the interruptions of service pertains to the broader phase of the subject, namely the actual delay encountered in the mine by power being shut off even for periods as short as that required to start up the transforming apparatus after being shut down by even a momentary line disturbance. A loss of seven days total during a year on this basis is not a serious reflection on the central station power supply. Granted, however, that it is somewhat high, the figures I mentioned were not intended to be exact, but for the purpose of illustration, the same as the figures given by the writer of the paper under discussion.

Wilfred Sykes: I was rather surprised at the statement regarding the dangers of interruption, and I will say that in a large power plant with which I am acquainted, which supplies approximately 75 per cent of the industries of two counties, all kinds of loads, over long lines, the percentage of the time it was ready to supply power was 99.98 per cent over a year; that is, there was only 2/100 per cent of the time when it was not ready to supply power to all the customers. A certain portion of the time the customers knew they could not get the power, due to the changing of poles and because of other changes in the line, and the total time during which the power was off altogether was twenty minutes out of 8760 hrs.

The point has been brought up as to the removal of the worry incident to a power plant. I do not think anybody who has had anything to do with mining work will doubt that there is much less worry involved in looking after motor-generator sets than in looking after an isolated generating station; in fact, a great many of the operators will tell you that they are quite willing to pay an appreciable amount if they could have this worry off their minds. They complain all the time about the power plant giving trouble. I think the importance of this question would be appreciated by anybody when you consider the increasing number of central stations that are being erected simply to supply power to mines. There are now in the course of erection quite a number of large plants, some to utilize water power and others are steam plants.

I do not think Mr. Bright brought out clearly enough in his paper that these figures, although of course only applying to a particular case and used for illustration, are based upon a great many investigations, and by some mysterious means he has managed to get the coal operators to open their books to him. I do not know how he did it, but he did it, and found out what their costs were, and consequently he has been able to obtain a great many data on which this paper has been based.

The question of putting in a central power plant for a group of mines is very often raised as a question of finance. I know of a number of cases in which the operators are quite willing to pay as much for central station power as they could generate that power for, themselves, for this reason: suppose they had to spend $300,000 or $400,000 for a central power plant, it will enable them to use that $300,000 or $400,000 in exploiting their regular business and that is, naturally, a very important thing, and they would rather enlarge their mines, spending that money in increasing their output, than put it into a central power plant just for the sake of running their mines.

W. N. Ryerson: There is one other point I do not think has been brought out in regard to this discussion of supplying central station power to diversified industries, and particularly a number of mines that may be within easy distributing distance of one another. That is the ability to operate a part of the equipment without the heavy expense necessary to operate localized plants; in other words, if you have a transformer station, it requires little or no attendance, and if for any reason some of the mines should shut down you can operate the remaining ones at very much lower cost than would be the case if you had to have practically a full crew operating your central power plant.

Then there is another question in regard to the reliability of service from central stations. A pretty good test of that is the requirements of the fire underwriters in regard to the use of electric fire pumps. If you comply with their requirements, and apply that test to your service and pass the inspection successfully, I think you can safely say that the service is reliable.

H. N. Müller: What are the interruptions on local plants as compared to unavoidable interruptions on energy delivered by transmission lines?

How is the figure of 18 days per month obtained for average mine working? Does this include two shifts a day, and shutdowns due to strikes, car shortage, etc., and what would be the effect of the same on, say, a five-year average month? What is the value of flexibility of central station energy in obtaining greater capacity in a short time?

What percentage of voltage regulation on the secondary of the transformer is permissible in this work, and what is the power factor of this load?

Graham Bright: Mr. Dreyfus has brought out certain conditions which may be met in a mine, but conditions at different mines vary so widely that it is impossible to lay down a set of rules to suit all conditions.

Mr. Dreyfus gave some interesting figures in regard to costs of operation at various load factors. He carries the load factor up to 75 per cent, which is far beyond anything that can be obtained at the average mine. He also bases some of his figures on the assumption of good management. In actual operation we seldom get good management in regard to the power supply, since those in charge wish to spend most of their time in mining and shipping coal, and the power plant is left largely to take care of itself until a breakdown occurs and then every person available comes in and works until the trouble is corrected.

I think Mr. Wood brought out very clearly the fact that even with the same cost or greater, it pays a mine operator to purchase central station power. Mr. Wood has been connected with mining work for a number of years and his opinion on this subject should carry great weight.

In regard to Mr. Gassman's remarks about there not being much in the " worry and care " being removed, I think that no person will question the statement that the " worry and care " of a substation operating from synchronous converter or motor-generator sets, is not to be compared in any way with the " worry and care " which exists with the average mining plant with boilers, engines and piping in the condition that they are usually found in. These plants as a rule are unable to carry overloads of any appreciable amounts, while a modern substation will take care of overloads up to 100 per cent with no trouble. Mr. Gassman mentions the fact that the central station power need be off the line only seven days in a year to wipe out the saving which has been shown. I believe that a large power company which has power off the line for seven days in one year would be considered very inefficient, and you will find that most of the larger power companies would consider this an extremely bad record.

As Mr. Sykes brought out, the figures given in my paper are not theoretical, but are really based on actual facts obtained from a great many mines which had been investigated during the last few months.

Mr. Müller has asked a question in regard to the power factor and voltage regulation of the power system. A fairly good power factor is generally obtained by taking the supply of direct current for the mines through synchronous converters or synchronous motor-generator sets. These machines can be set for a leading power factor and will tend to compensate for the induction motors which are used for driving the fans and pumps. The question of voltage regulation does not come up very frequently, since the mine operator as a rule is satisfied if he gets plenty of power at a fairly steady voltage. The lighting about a mine is of such a nature that close voltage regulation is not usually insisted upon.

A paper presented at the Boston Section Meeting of the American Institute of Electrical Engineers, Boston, Mass., May 15, 1912.

NOTES ON UNDERGROUND CONDUITS AND CABLES

BY C. T. MOSMAN

The consideration of an underground conduit and cable system involves many points of interest besides that of the physical construction of the duct line, manholes, etc. The point of prime importance and interest is the load or current which may be safely carried through a duct, and this is intimately related to nearly every feature of construction of the duct system and of the cables.

The heat generated in the cables results principally from I^2R loss in the copper, but in the case of single-conductor cables carrying alternating currents may be considerably augmented by I^2R loss in lead sheaths, and slightly by dielectric hysteresis in the insulation.

The I^2R loss of large sizes of cable will be greater for alternating than for direct currents, due to the effective increase in resistance resulting from skin effect. Cables of 1,000,000 cir. mils or larger and for use on sixty-cycle service should be provided with a hemp core, to reduce the skin effect to a negligible value.

This heat will be dissipated by conduction through the duct structure to the surrounding earth; by conduction along the copper lead to the manholes, and there dissipated by the ventilation, if any; by air currents through the ducts from manhole to manhole. There will be a continuous fall of temperature through the various mediums from the copper to the earth, so that additions must be made to any exterior temperature in order to arrive at the temperature of the copper.

The advisable limit of temperature of the copper differs according to the type of insulation used and the voltage impressed thereon. To avoid undue deterioration, rubber insulation should not be operated above 50 deg. cent. and varnished cambric or paper insulation above 80 deg. cent., and this latter figure should be understood to apply only to low-potential operation.

The insulation resistance of insulating material varies with the temperature, and differently for different insulations. The rate of decrease of insulation resistance, with increase of temperature, of high-quality rubber insulation is much lower than is the case with either paper or varnished cambric, the rate of decrease of paper being about four times that of good rubber, and the rate of varnished cambric about eight times.

The variation of resistance to puncture with variation of temperature is of much more importance than the variation of insulation resistance. The puncture resistance varies with the time of application of the potential. The instantaneous resistance to puncture of varnished cambric insulation is the same hot or cold, but above a critical temperature of 70 to 80 deg. cent. the sustained puncture resistance decreases with increase of temperature, while below 60 deg. cent. this effect is negligible. This effect seems to depend upon variations of dielectric hysteresis with temperature and it varies in percentage with the thickness of insulation.

This effect is not of practical moment in the case of cables built for operation at 2000 volts or less. With cable built for 2500 volts the effect may be approximately 5 per cent, with 10,000-volt cable about 20 per cent, and with 25,000-volt cable about 25 per cent.

It should be noted that the above-stated decreases of puncture resistance exist only while the high temperature exists, the insulation regaining its normal resistance when cooled.

Paper insulation is subject to the same effect, but to a somewhat lesser degree.

Rubber insulation maintains its normal value of puncture resistance much better than either paper or varnished cambric, but suffers a permanent deterioration.

Consideration of the above indicates that it would be conservative to limit the copper temperature of high-tension cable to 50 deg. cent. for any of the above types of insulation.

The thermal drop through the insulation will vary with the character and thickness of the insulation and the temperature of the copper, and the rate of dissipation of energy. Tests have been made on various types of insulation used on generator coils to determine the thermal drop. The results of tests by different experimenters differ widely.

One set of tests gives values of thermal drop in degrees centigrade per inch thickness of insulation, per watt per square inch dissipated, of 169 for varnished cambric tape at the rate of 0.30 watts per sq. in. (6.45 sq. cm.), and 136 at the rate of 1.63 watts per sq. in. (6.45 sq. cm.) From these figures it would appear that at rates of radiation common in cable practise the thermal drop would be in excess of 169 deg. cent. per watt per square inch per one in. (2.54 cm.) thickness.

Applying the above to a varnished cambric insulated cable with a rate of 0.05 watts per sq. in. (6.45 sq. cm.) and insulation of 11/32 in. (8.7 mm.) thickness, the copper may be expected to be at about 3 deg. cent. higher temperature than the surface of the cable, thus showing that this is not an important matter in connection with the average commercial cable. The drop in temperature through the air in a duct and along the length of the duct will depend upon the opportunity for a definite circulation of air through the duct, which will usually be negligible. The temperature drop through the duct structure will doubtless vary with the type of conduit, whether tile or fiber, and with the degree of dampness of the surroundings.

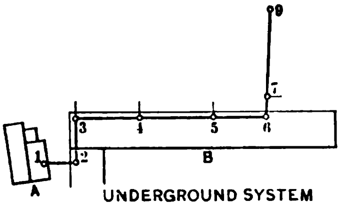

Fig. 1

The position of the individual duct in the system will have great effect on its temperature elevation, the ducts next to earth at the bottom and sides being the coolest and those furthest removed from earth the warmest.

The foregoing must serve as my excuse for thinking that a reference to some actual tests made on a conduit system may prove of interest.

A manufacturing plant installed a conduit system in the mill yard, using fiber conduit laid in cement. Because of physical limitations the 81 ducts were laid nine wide and nine deep. Only a few cables were at first installed, but when later it became necessary to add to the number, it seemed wise to investigate somewhat before deciding upon the cable size and the permissible load per cable.

The main conduit line extends from manholes No. 1 to No. 9 as shown in Fig. 1.

Referring to Fig. 3, giving a section of the conduit line, it will be noted that all the cables installed are single-conductor

1,000,000-cir. mil, paper-insulated, except those in ducts 13, 14 and 15, which are 500,000-cir. mil single-conductor, rubber-insulated.

Of the total length of main conduit line, the sections between manholes No. 1 and No. 2, and manholes No. 7 and No. 9, are the only sections which are actually underground. The balance, between manholes No. 2 and No. 7, are above the basement floor level in one of the buildings; the lower row of ducts being some ten to twelve in. (25 to 30 cm.) above the floor level.

The latter sections, being inside the mill basement, with three sides of the system exposed to air, may be expected to operate at higher temperatures than the former sections, which are buried in moist earth. Further, these sections may be expected to have always a greater number of ducts occupied by loaded cables than sections 7 to 9. The limit of the capacity of the duct system hence should depend upon the hottest portion of these indoor sections. Thermometers were placed on the lead sheaths of the cables at the duct ends in manholes Nos. 7, 6, 5 and 4.

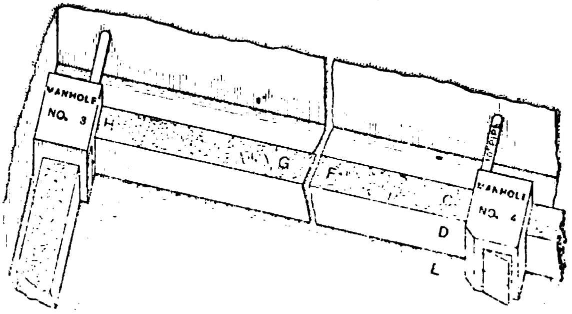

FIG. 2—THERMOMETER LOCATIONS, CONDUIT LINE, MANHOLES 3 to 4.

A—Earth in manhole No. 4.
B—Air entering " " " at vent pipe.
C—Top of duct line, as shown.
D—Side " " " " "
E—Earth near manhole, as shown.
F—Top of duct line, " "
G— " " " " " "
H— " " " " " "

Devoting a day to each manhole, readings were taken hourly of temperatures and loads of the cables.

The results of these tests indicated that the highest temperature would be obtained at manhole No. 4, and the section from manholes No. 3 to No. 4 was finally taken as the one representing probably the severest condition as to temperature.

This section is located in the basement of a building where there are a number of steam and water pipes and where the temperature is usually rather high, as compared with actual underground temperatures.

The section was tested under varying conditions of operation and ventilation. Thermometers were placed on the lead sheaths of all cables carried through manhole No. 4 at the point where cables left the ducts on the power house side, and readings taken of the ampere load on each individual cable, together with the temperatures. The iron drawing-in wires in all the ducts not containing cables were connected to a 125-volt direct-current source that could be operated and controlled independently of the other apparatus, and readings taken of the current flow and drop across the conductors in each pair of ducts, from which were calculated the watts loss per foot and the average temperature of the iron conductor, a sample of the iron wire having previously been carefully tested and a temperature-resistance curve obtained throughout a wide range of temperature, as shown in Fig. 4.

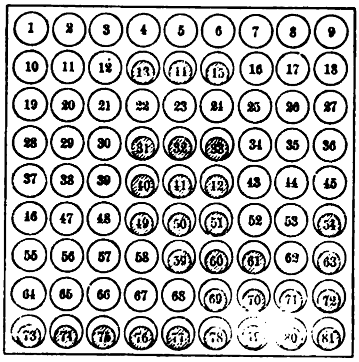

FIG. 3—SECTION OF CONDUIT LINE, MANHOLES 3 TO 4.

Ducts 13-14-15 contain 500,000-cir. mil rubber cables. Balance of ducts containing cables have 1,000,000-cir. mil paper cables installed.

All other ducts except 16-22-58 contain 0.049 galvanized iron wire, which was used as conductor during test.

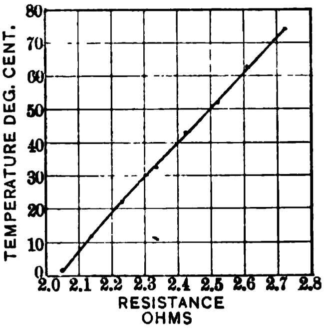

FIG. 4—RESISTANCE-TEMPERATURE CURVE.

18 feet 0.049 galvanized iron wire.

It was the intention to obtain the temperature of the conductor by means of the drop of potential method, and the temperature of the air in the duct by resistance test of the conductor with a Wheatstone bridge after cutting current off the conductors and allowing them a sufficient time to reach the temperature of the air in the duct. The only bridge available at this time was of the slide wire type with telephones in place of galvanometer, and sufficient inductance from cables carrying load was obtained, so that this method had to be abandoned.

Fig. 2 shows roughly the appearance of the section tested and the location of the thermometers on the exterior of the duct line, while Fig. 3 shows a cross-section of the duct line between manholes No. 3 and No. 4 looking toward manhole No. 3.

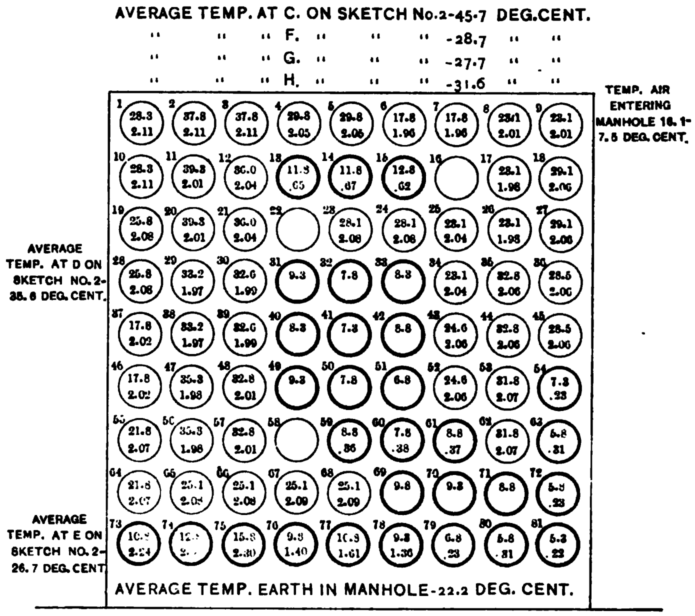

FIG. 5—TEST NO. 1, 11½-HOUR TEST, MANHOLE NO. 4, NATURAL VENTILATION.

Heavy circles denote ducts containing cables.
Upper figures in circles are temperature rise in deg. cent. above earth in manhoie.
Lower figures are watts loss per duct-foot, average for 11½ hr.
Small figures above circles are duct numbers.

TEST NO. 1

This test was made with natural ventilation to the manholes through the pipes to outside wall, shown in Fig. 2. The current was applied to the iron test wires at approximately two watts per duct foot during the regular operating period of the mill, that is, from 6:30 a.m. to noon and from 1:00 to 6:00 p.m. The results of this test are shown in Figs. 5, 6 and 7.

Fig. 5 shows the average watts loss per duct foot and the temperature rise above the temperature of the earth in the manhole, plotted as a cross-section of the conduit line. A study of the results indicated that considerable of the heat generated in the test wires must have been dissipated by the cables operating at low loads, as some of the temperatures near the center of the duct line were lower than some at the outside.

The maximum temperature rise was obtained in ducts No. 11 and No. 20, while the lowest maximum temperature rise in any duct containing test wire was obtained in ducts Nos. 6, 7, 37 and 46.

The low temperature obtained on the cables is due primarily to the fact that the temperatures given are sheath temperatures at the edge of the duct, while those of the test wires are average temperatures of the conductor throughout its length, and an average of two ducts, combined with the fact that the air entering the manholes through the ventilating pipes blows directly across the cables just as they leave the ducts, and also to the light loads carried by the cables during the test.

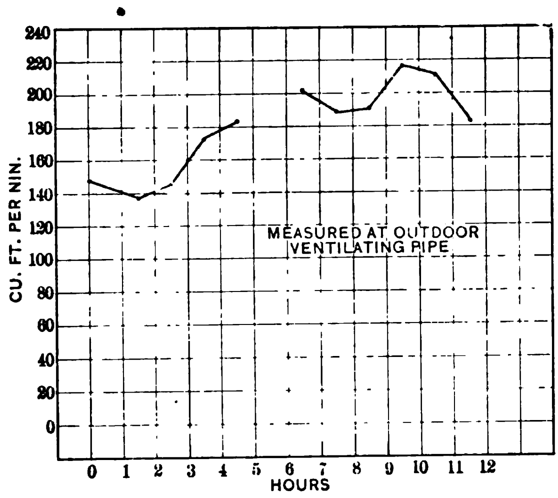

FIG. 6—VENTILATION, MANHOLE NO. 4, TEST NO. 1.

During this test and all others on this section of the line, there was a considerable draft of cold air blowing across the top of the conduit which came from the windows in the wall back of the conduit (see Fig. 2); the windows were not open and air blew in around the casings only. The test does not show, however, that this had any noticeable effect on the results obtained, except that there seems to be a tendency for the minimum temperature to be located slightly to the right of the center.

Test No. 2

This test is a duplicate of the previous one, except that all outdoor ventilation to the manholes was stopped off and the manholes opened for twelve hours before test was started and left open during test, so that the entire section of the conduit line might be of approximately the same temperature as the basement where it is located. This was done in an endeavor to approximate the conditions which it was assumed would be obtained in the summer months. It was found later, however, that summer conditions were not any more severe than in the winter, for the reason that windows in the wall back of the conduit line are then kept open and the temperature of the basement seldom exceeds the amount obtained during the winter months, so that test No. 1 shows approximately the results which may be expected at any time of the year in this section of the conduit. The rise in temperature above that obtained in test No. 1 was not of any considerable amount. The whole cross-section showed a slightly higher temperature and the temperature distribution was practically the same.

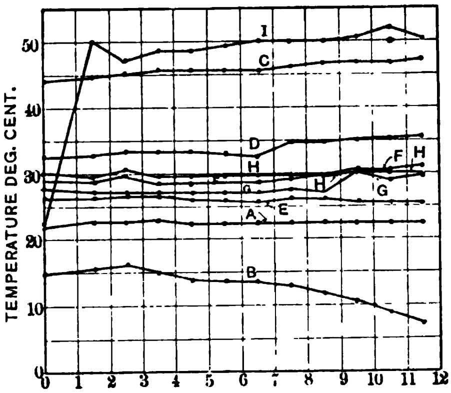

Fig. 7—Temperatures, Section from Manhole No. 3 to No. 4. Natural Ventilation. Test No. 1.

A—Earth in manhole No. 4.
B—Air entering " " " through ventilator—See Fig. 2.
C—Top duct line, see Fig. 2.
D—Side " " " " "
E—Earth near manhole, see Fig. 2.
F, *G*, *H*—Top duct line, " " "
I—Conductor (iron wire) center duct in top row.

TEST NO. 3

This test, except as to duration, is a duplicate of test No. 1. In this case the test was extended in order to approximate the results liable to be obtained if it became necessary to operate overtime. The results are shown in Figs. 8, 9, 10 and 11.

During the test the manholes were ventilated in the regular manner and the supply of air measured as shown in Fig. 9. In this particular case there was a strong draft of air through all vacant ducts, of which there were 57, from manhole No. 5 to No. 4.. This has been taken into account in plotting the results, so that the record gives the total amount of air supplied to manhole No. 4, with the exception of the quantity which came in from manhole No. 5 through the 24 ducts containing cables. It is doubtful if this condition will be found in practical operation as it seems extremely unlikely that the whole system would operate overtime on the same date.

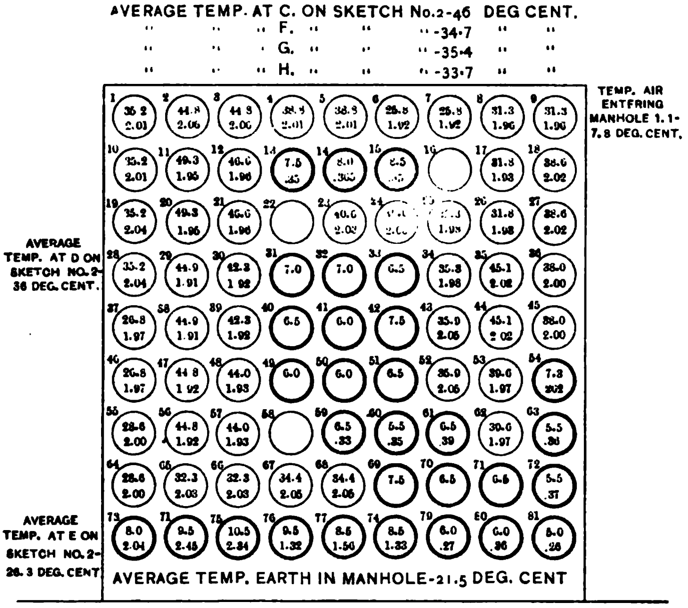

FIG. 8—TEST NO. 3, 30-HOUR TEST, MANHOLE NO. 4, NATURAL VENTILATION.

Heavy circles denote ducts containing cables.
Upper figures in circles are temperature rise in deg. cent. above earth in manhole.
Lower figures are watts loss per duct-foot, average for 30 hr.
Small figures above circles are duct numbers.

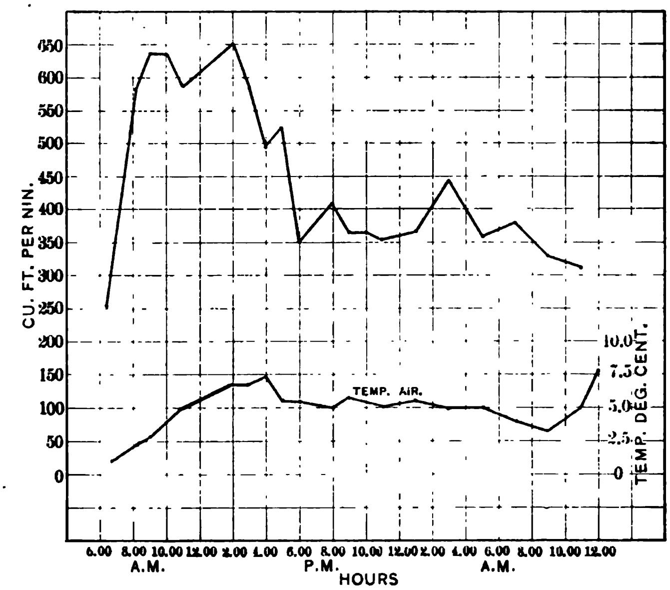

FIG. 9—VENTILATION, MANHOLE NO. 4, TEST NO. 3.

Measured at ventilating pipe and also ducts to manhole No. 5—about equal quantities of air from each source.

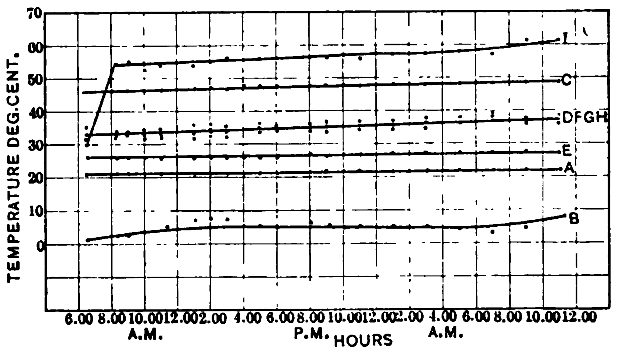

FIG. 10—TEMPERATURES, SECTION FROM MANHOLE NO. 3 TO 4, NATURAL VENTILATION. TEST NO. 3.

A—Earth in manhole No. 4.
B—Air entering " " "
C—Top of duct line—see Fig. 2.
D—Side " " " " " "
E—Earth near manhole— " "
F, *G*, *H*—Top of duct line " "
I—Conductor, center duct, top row.

The tests so far described show only average temperatures and give little basis for determining the temperature at the middle point of a duct or throughout its length. To investigate this distribution a number of copper resistance coils were made up and inserted in various ducts. The coils were of circular cross-section, wound with fine copper magnet wire upon a wooden mandrel and enclosed in a sheet copper envelope, after which they were dried and thoroughly impregnated with paraffin in such a way that the containing envelope was entirely filled. This was done with the intent to render the coils waterproof, and to reduce the thermal resistance so that rapid tests could be made. Each coil was supplied with four leads, two of which were soldered directly to the winding, the other two being merely soldered together inside the coil casing and used to determine the resistance of the coil leads so that the resistance of leads might be deducted from coil resistance measurements. All resistance measurements were made by a portable decade set. A temperature-resistance curve of each test coil was made, and used as a basis for temperature determinations of ducts.

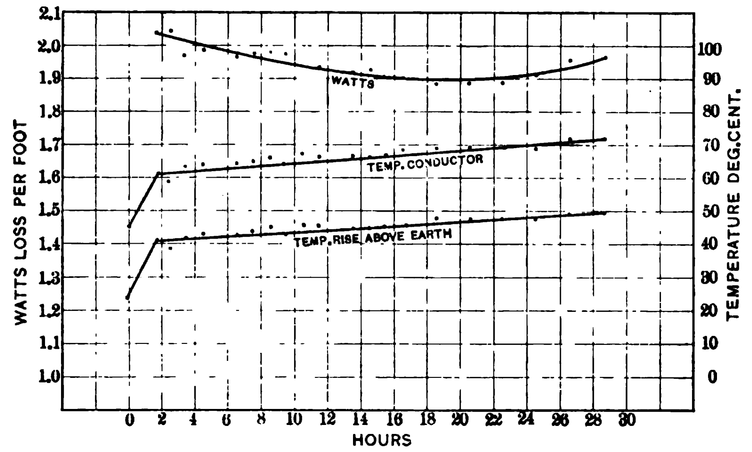

FIG. 11—TEMPERATURE, DUCTS 11 AND 20, TEST NO. 3.

Before making test for temperature distribution in the length of ducts, it was decided to place the test coils midway between manholes No. 3 and No. 4 and determine what, if any, temperature variation there was in the cross-section of the conduit system due to the normal loads on the cables installed, with no load on iron wires. This was done and the following Table I gives the results obtained:

TABLE I

Time	Temperatures, deg. cent.				Duct Nos.					
	2	5	20	35	3	45	56	62	68	74
9:00	22.3	21.5	22.7	22.7	22.4	21.5	21.3	23.6		30.8
10:00	22.7	21.7	23.0	22.7	22.4	21.5	23.1	23.8		31.4
11:00	22.7	21.7	23.0	22.9	22.4	21.9	23.1	23.8	26.3	32.1
12:00	22.7	21.7	22.7	22.9	22.2	21.9	23.1	24.0	26.4	32.4
1:00	22.0	20.6	22.3	22.3	21.3	21.1	22.9	24.0	26.4	29.0
2:00	22.3	21.2	22.5	22.3	22.2	21.5	23.1	24.3	26.7	31.1
3:00	22.3	21.7	22.7	22.5	22.2	21.9	23.6	24.3	27.0	32.2
4:00	22.3	21.7	22.7	22.5	22.2	21.9	23.6	24.3	27.0	32.2
5:00	22.3	21.7	22.7	22.5	22.2	21.9	23.6	24.5	27.9	33.4

One coil was placed in duct No. 2 (refer to Fig. 3), which is exposed to the air on one side and surrounded by vacant ducts on the other three sides; this shows practically no temperature variation.

Four coils were placed, one in each of the ducts Nos. 20, 35, 38 and 56, which were surrounded on all sides by vacant ducts; except for No. 56 these showed little temperature variation except for a slight cooling due to the noon shutdown.

A coil was placed in duct No. 5, which is exposed on one side to the air, on the opposite side to a duct containing a cable, and on the other two sides to vacant ducts; this showed practically no variation except at noon, and was at a generally lower temperature than those mentioned above, probably due to the proximity of cables operating at very light loads. The lead sheaths of these cables presumably conducted heat to the ends of the ducts and dissipated it to the air in the manholes.

A coil was placed in duct No. 45, which is situated quite similarly to No. 5, the adjacent cable carrying a very light load.

Two coils were placed one in each of ducts Nos. 62 and 68, which were surrounded on all but one side by ducts containing cables carrying loads, there being a vacant duct on the remaining side these show a higher temperature and slightly more variation.

One coil was placed in duct No. 74, which contained a cable carrying an average load of 410 amperes; this shows a higher temperature than any of the others, as should be expected, and by comparing with the temperatures by thermometer of the lead sheath at the manhole it was seen that at the middle point of the duct the temperature was 18 per cent higher with 20 per cent less current in the cable.

Duct No. 56, though surrounded by vacant ducts, shows a higher temperature than ducts Nos. 20, 35, and 38, similarly situated; this is probably due to the heat from ducts Nos. 73, 74, and 75 rising through the duct structure.

The temperatures shown by this test are low and the variations negligible, due to the small loads carried by most of the cables at the time, and the large number of vacant ducts.

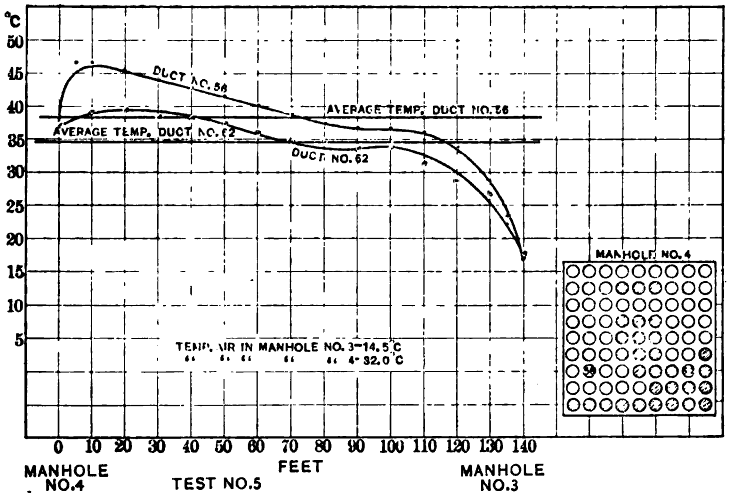

FIG. 12—TEMPERATURE—LENGTH. MANHOLES 3 TO 4.

Ducts Nos. 56 and 62. After 24 hours of continuous operation at 2 watts per foot loss. Velocity of air 2.5 ft. per second, natural ventilation. Ducts 3 in. diameter. 8.8 cu. ft. of air per minute.

Worked from center to manhole No. 3, then from center to manhole No. 4, the temperature essentially constant during the test.

TEST NO. 5

In order to determine the resulting effect of an air circulation through the ducts containing test wires, all openings to basement in manhole No. 3 were closed, as well as all openings to outdoor air in manhole No. 4, so that a measurable circulation of air from manhole No. 3 to No. 4 through ducts containing test wires could be obtained. The test wires were operated at two watts per duct foot for 24 hours before taking readings.

The distribution of temperature throughout a duct was obtained by resistance readings on a test coil at various positions in the duct, with constant load on the iron wire.

The distribution of temperature in ducts 56 and 62 is shown in Fig. 12. This figure clearly brings out the advisability of surrounding a heavily loaded cable with others carrying light loads, as the conductor in duct No. 62, surrounded on three sides by cables, operated at a lower temperature than that in duct No. 56, surrounded by conductors carrying equal loads.

It is to be noted that the maximum temperature in duct No. 62 is 13 per cent greater than the average, while the maximum in duct No. 56 is 21.4 per cent greater than the average. It is, therefore, reasonable to assume that the temperatures obtained in tests Nos. 1, 2 and 3 should be increased approximately 15 per cent to obtain the approximate maximums, as the values given were obtained by calculation from the drop across a test wire, which must necessarily give average values.

TEST No. 6

It was found in the previous test that the maximum temperatures occurred at approximately 15 ft. (4.5 m.) from manhole No. 4 when using natural draft. On that account all of the test coils were located at that position in this test. Previous to the commencement of this test the ducts containing test wires were operated at two watts loss per foot for 48 hours, while the ducts containing cables operated at their usual loads. The temperatures attained by the air in the ducts 15 ft. (4.5 m.) from manhole No. 4 are shown in Table II.

While not entirely consistent, a comparison of this table with duct locations shown in Fig. 3 shows the influence of lightly loaded cables in adjacent ducts. A comparison with Fig. 12 shows that in 24 hours the ducts arrive at practically a constant temperature with natural ventilation when loaded to two watts per duct foot by the iron wires.

TABLE II

Duct. No.	Temperature 15 ft. (4.5 m.) from manhole No. 4
2	41.5 deg. cent.
5	45.0 " "
20	52.5 " "
35	51.5 " "
38	51.5 " "
45	42.5 " "
56	50.0 " "
62	41.0 " "
68	45.5 " "

At 8:30 a.m. forced draft was applied, the input to blower motor being 2.2 kw., and readings taken until 10:30 a.m. The results

are sufficiently indicated by Fig. 13. It was noted that at the completion of the test the average temperature of all ducts was approximately 25 deg. cent., and the temperature rise above incoming air 20 deg. cent. This indicates the feasibility of operating the system at greater loads by the application of forced draft. It does not, however, give any indication of what air pressure would be required, as in this test the large combined area of the vacant ducts was equivalent to the blower exhausting to the free atmosphere. Possibly less volume of air would be required to carry off the same heat if the ducts contained cables, because of the large area of cable sheath surface to come in contact with the air.

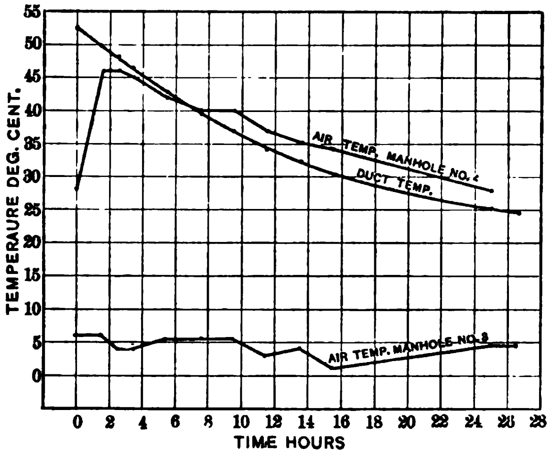

FIG. 13—TEMPERATURE VARIATION WITH FORCED DRAFT, DUCT NO. 20. TEST NO. 6.

After 48 hours' operation at 2 watts loss per foot, 475 cu. ft. air per minute at a velocity of 13.8 ft. per second. Duct temp. taken by resistance coil in duct 15 ft. from manhole No. 4.

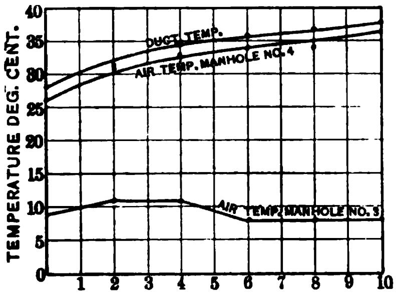

FIG. 14—TEMPERATURE VARIATION WITH FORCED DRAFT, DUCT NO. 35.

At 4 watts loss per foot, and 500 cu. ft. of air per minute. Duct temperature obtained with resistance coil in duct 15 ft. from manhole No. 4. Test No. 7.

TEST NO. 7

As soon as test No. 6 was completed the forced draft was shut off and connections on test wires changed so that four watts loss per foot could be obtained and test No. 7 started at 11:30 a.m., running to 9:30 p.m. The results are sufficiently indicated by Fig. 14. The maximum temperature rise above incoming air in no case exceeded 30 deg. cent. under these conditions. It therefore seems that, taking into account the relief afforded by noon shutdown, the system may be operated at four watts loss per foot of duct, provided it is possible to force a sufficient amount of air through ducts containing cables. Unfortunately no test was made to determine the air required to cool a duct containing a cable, or the pressure necessary to force that air through, as might have been done by plugging up all vacant ducts and measuring the air delivered from manhole No. 4.

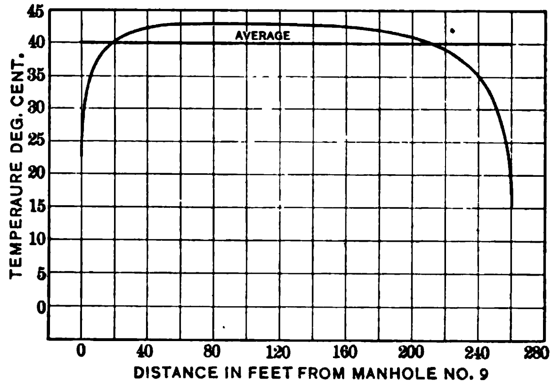

FIG. 15—TEMPERATURE VARIATION, CENTER DUCT, BETWEEN MANHOLES NO. 7 AND 9, TEST NO. 9.

After 24 hours' operation of all ducts containing wires of 2 watts loss per foot. This duct contained no wire or cable.

Temperatures in deg. cent.

Manhole No. 7		Manhole No. 9	
Earth temp., top	— 17.4	Earth temp., top	— 17.4
" " bottom	— 16.3	" " bottom	— 16.3
Av. manhole temp.	— 15.1	Av. manhole temp.	— 16.8

Average temp. for line—16.0

TEST NO. 9

Every test on the section of conduit line from manhole No. 3 to No. 4 brought to light more clearly the fact that no accurate deductions as to temperature conditions could be made from the tests, on account of the dissipation of the heat produced by the test wires through the cables operating at light loads. On that account arrangements were made to have further tests on the section of conduit line from manhole No. 7 to No. 9, which contained but six cables, located in the lower right-hand corner of the line when viewed from manhole No. 9, *i.e.*, ducts 70, 71, 72, 79, 80 and 81, Fig. 3. The main conduit line ends at this manhole and only a short length of duct exists between the opposite side of the manhole and the outdoor air where the cables are suspended from the underside of a bridge structure. During the tests in this section all ducts leading to the outdoor air were tightly closed to eliminate any air circulation that existed.

The iron drawing-in wires were used for heating in this section as in the previous tests, and the connections were so made that all ducts except the center one and the six containing cables were heated.

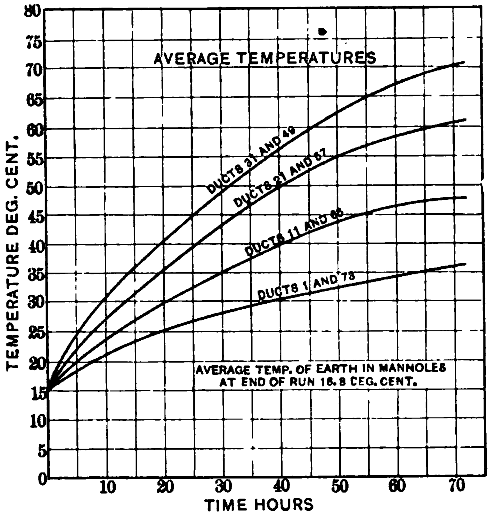

FIG. 16—TEMPERATURE VARIATION IN CROSS-SECTION OF CONDUIT LINE DURING CONTINUOUS RUN OF 72 HOURS.

At 2 watts loss per foot. Manholes 7 to 9. Test No. 10.

The first test consisted of measurement of the temperature throughout the length of the center duct with a resistance coil to determine the point of highest temperature. The results are shown in Fig. 15. It is to be noted that the temperature at manhole No. 9 is five degrees higher than at No. 7. This is believed to be due to the presence of the test connections and the operator at No. 9, but principally to the general tendency of the draft to be from No. 7 to No. 9.

This figure again shows the advantage of resistance coil test of temperature over the drop of potential in the iron conductor method, as the maximum temperature is 6 per cent in excess of the average.

It was expected that this test would establish an approximate rule for the per cent to increase the values obtained in section between manholes No. 3 and No. 4, which were made by the drop of potential method in the iron wires, but as this shows only 6 per cent increase, while previous tests on the previously mentioned section indicated an increase of from 13 to 21 per cent, it was concluded that undoubtedly the larger values were more nearly correct for that section, as the temperature of the exterior of concrete envelope in the basement must of necessity be higher than when underground.

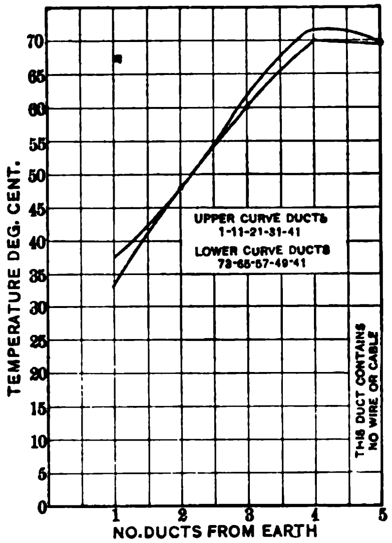

Fig. 17—Temperature Variation in Cross-Section of Duct Line, Manholes 7 to 9.

After 72 hours' continuous operation at 2 watts loss per foot. Test No. 10.

Test No. 10

In order to get this section of the conduit line into a condition approximately equal to what would be obtained during the summer months with the line full of cables, current was maintained at two watts loss per duct foot on the iron wires continuously for 72 hours, during which time readings were taken on the resistance coils, which were located approximately midway between the two manholes. Figs. 16 and 17 have been plotted from the results.

In Fig. 16 is plotted the average of the temperatures of two ducts similarly situated.

Fig. 17 shows the temperature variations in the cross-section of the conduit. It is to be noted that there is little difference between the two curves.

Test No. 11

After the completion of the previous test the current was cut off from the iron wires and the conduit line allowed to cool off for 48 hours, when current was again applied and maintained for one week at two watts loss per foot in exactly the same manner as would be the case if this section were carrying the regular mill load with each duct containing a cable. The results are shown in Figs. 18, 19, 20 and 21, which show the maximum temperature is not reached until the evening of the fifth day. At that time the average temperature of the earth was 17.5 deg. cent., so that the temperature rise of the hottest duct was 49 deg. cent.

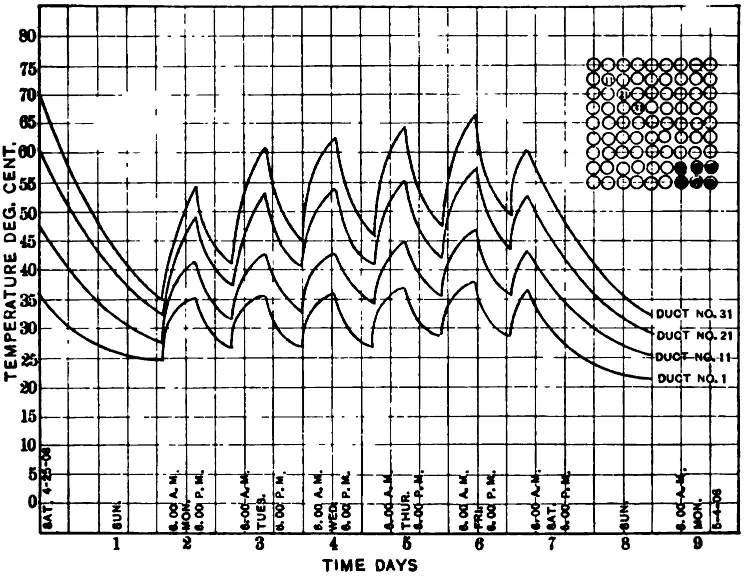

Fig. 18—Temperature Variation, Normal Running Condition, for One Week.

At 2 watts loss per foot. Between manholes 7 and 9. Test No. 11.

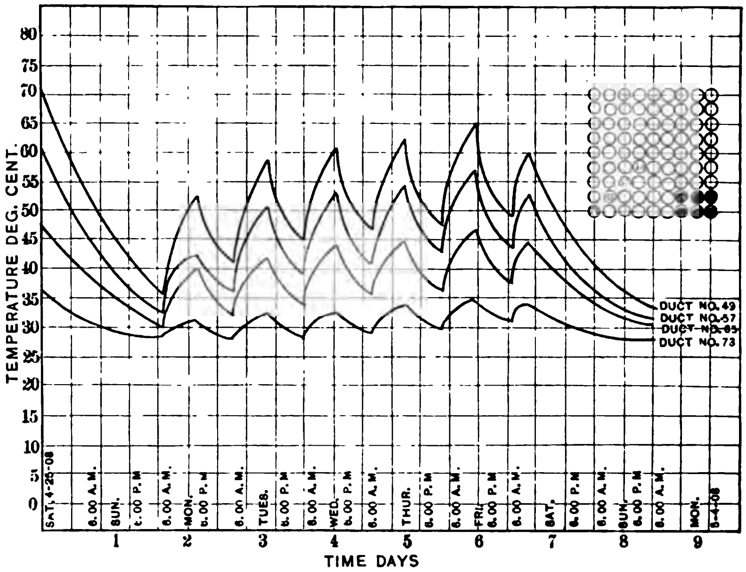

FIG. 19—TEMPERATURE VARIATION, NORMAL RUNNING CONDITION, FOR ONE WEEK.

At 2 watts loss per foot. Between manholes 7 and 9. Test No. 11.

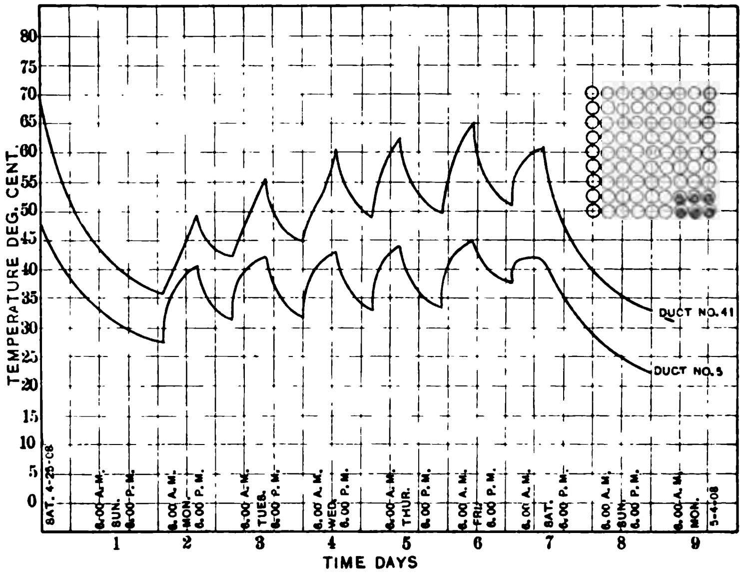

FIG. 20—TEMPERATURE VARIATION, NORMAL RUNNING CONDITION, FOR ONE WEEK.

At 2 watts loss per foot. Between manholes 7 and 9. Test No. 11.

Test No. 12

The preliminary tests showed that the cable in duct 76 was four degrees warmer than the one in duct 74 with 27½ per cent less load. This, in view of the fact that all the cables were bonded together in manhole No. 3, indicated that undoubtedly the removal of the bonds would result in increased carrying capacity for the same temperature. In order to determine the probable values of sheath currents, tests were made both on cables already installed and on cables especially arranged for that purpose.

Two short lengths of 1,000,000-cir. mil cable were placed in short lengths of conduit and connected as shown in Fig. 22, cable *A* being 13/64 in. (5.15 mm.) rubber and 3/32 in. (2.38 mm.) lead, over-all diameter 1.738 in. (34 mm.), and cable *B* being 4/32 in. (3.17 mm.) paper and 4/32 in. (3.17 mm.) lead, over-all diameter 1.645 in. (31.8 mm.). Thermometers were placed on the copper core by means of a hole drilled through both the sheath and insulation. The hole was made somewhat larger than the thermometer bulb and all vacant space tightly packed with asbestos fiber. This method of getting the copper temperature is somewhat crude, but as no instruments suitable for other methods were available, it was used.

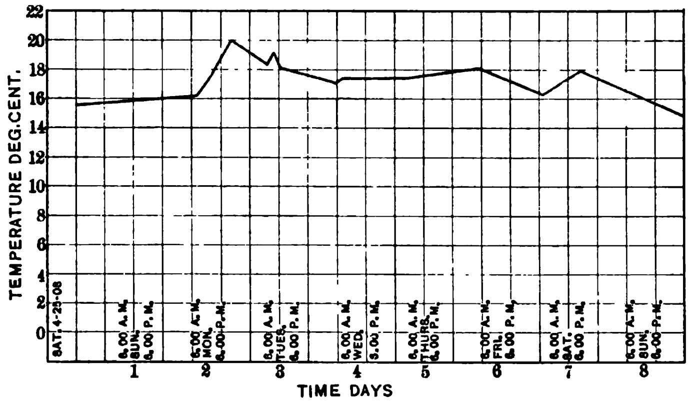

Fig. 21—Average Temperature, Earth, Manholes 7 and 9, Test No. 11.

Thermometers were also placed on the sheath of the cables and the outside surface of the conduit. The temperature of the air in the duct was obtained by means of resistance coils suspended inside, out of contact with either conduit or cable.

The sheath currents obtained are shown in Figs. 23 and 24.

Curve 1 of Fig. 23 gives the actual values of sheath current obtained on the test of the short lengths of cables, and curve 3 gives the calculated value upon deducting the resistance of the ammeter and bond contacts measured by a bridge, while curve 4 gives the value which would have been obtained with negligible bond and ammeter resistance and both cables having the same cross-section of lead as the paper-insulated cable.

Curve 2 is the average of several tests made on the sheaths of cables in No. 1 and No. 2 spinning-room circuits. These cables are solder bonded in manhole No. 3 approximately 275 ft. (83.8 m.) from the power house, where readings were taken by means of an ammeter and clamped bonds. Undoubtedly this curve gives the most reliable information, as it was made up from the tests of actual working conditions.

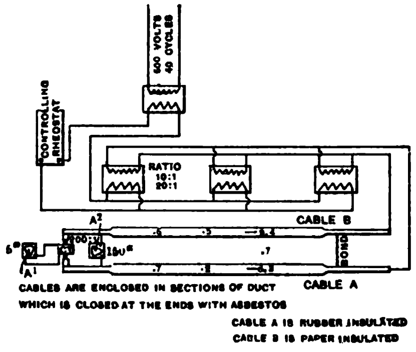

FIG. 22—DIAGRAM OF CONNECTIONS IN TEST OF VARIATION IN TEMPERATURE AND BONDING OF 1,000,000-CIR. MIL CABLES.

Thermometers:—1-lead sheath, cable *A*; 2-copper, cable *A*; 3-lead sheath, cable *A* 4-lead sheath, cable *B*; 5-copper, cable *B*; 6-lead sheath, cable *B*; 7-air; 8-outside of duct, cable *A*; 9-outside of duct, cable *B*.

Fig. 24 shows the watts loss per foot of conductor in both sheath and copper, as well as combined loss. In making up this curve the values of sheath loss were calculated from current values shown in curve 2 of Fig. 23, using a resistance per foot of lead sheath of 0.000182 ohms at 20 deg. cent. These curves illustrate the necessity of keeping the lead sheaths of single-conductor cable carrying large alternating currents from contact.

Figs. 25, 26, 27 and 28 show the temperature results of the tests on the experimental cables, Figs. 25 and 26 on the paper cable, and Fig. 27 and 28 on the rubber.

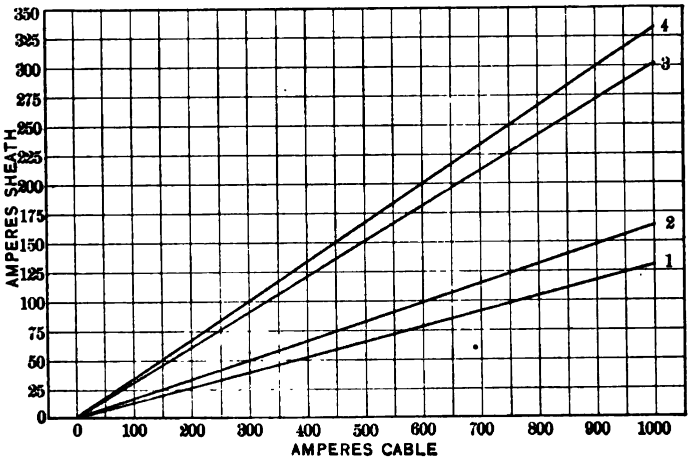

FIG. 23—SHEATH CURRENTS IN BONDED CABLES—TEST NO. 13.

1—Test on 17 ft. 1,000,000 cir. mil cable.
2—Test on Nos. 1 and 2 spinning-room circuits.
3—No. 1 corrected for bond resistance.
4—No. 3 corrected to basis of sheath of paper cable.

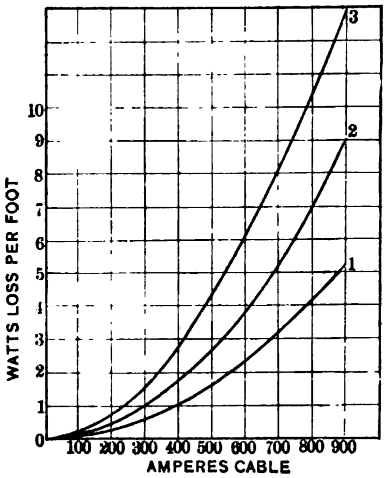

FIG. 24—WATTS LOSS PER FOOT, 1,000,000-CIR. MIL CABLES.

1—Sheath loss.
2—Copper loss.
3—Combined loss.

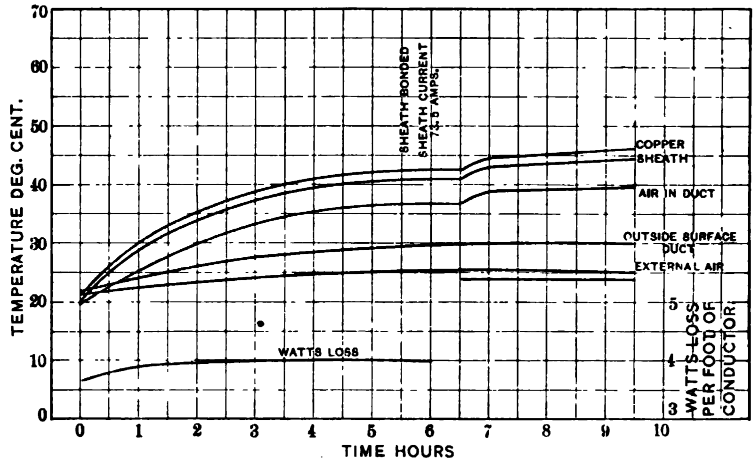

FIG. 25—TEMPERATURE OF 1,000,000–CIR. MIL CABLE.
4/32 in. paper, 4/32 in. lead. In conduit, at 600 amperes. Test No. 12.

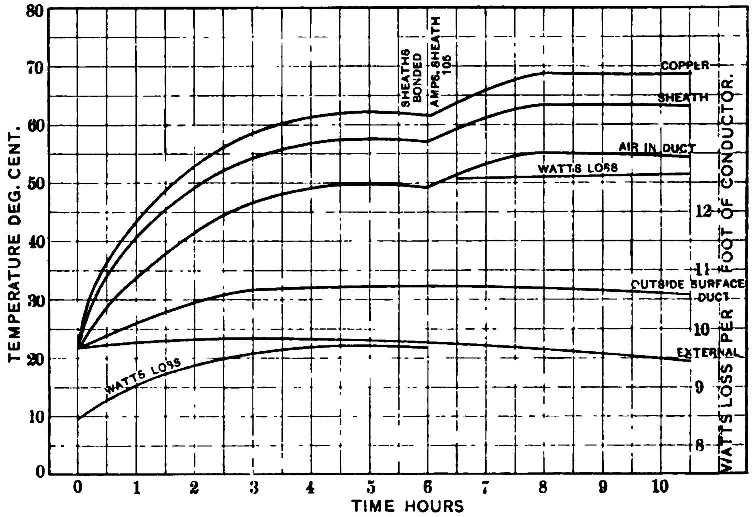

FIG. 26—TEMPERATURE OF 1,000,000–CIR. MIL CABLE.
4/32 in. paper, 4/32 in. lead. In conduit, at 900 amperes. Test No. 12.

These curves are principally of interest in showing the distribution of the thermal drop through the various insulating mediums from the copper to the outside air.

Due to the thinness of the insulation adjacent to the copper the thermal drop therein is small, but it agrees fairly with more careful determinations made on various kinds of insulation on coils.

Due to the tests detailed in this paper being almost entirely based on heat generated in iron wires and in ducts containing only the iron wire, and hence having very different radiating and ventilating characteristics from ducts containing commercial cables, it is difficult to establish therefrom a limit to the safe loading capacity of the ducts. However, taking into account the fact that the sheath of a cable will transmit considerable heat to the duct end and thereby more or less offset the better ventilation of a duct containing only an iron wire, and that the curves show practically constant temperature in the duct with only iron wires, except near the ends and the low temperatures shown by the tests, and allowing for the cooling effect of the noon and night shut-downs, it seems safe to conclude that any portion of the conduit line may be safely operated at about 2.5 watts loss per foot of duct with natural ventilation and at about 4 watts loss per foot with sufficient forced ventilation, provided all lightly loaded cables are located at the center of the conduit, with the heaviest loaded cables in the outside ducts.

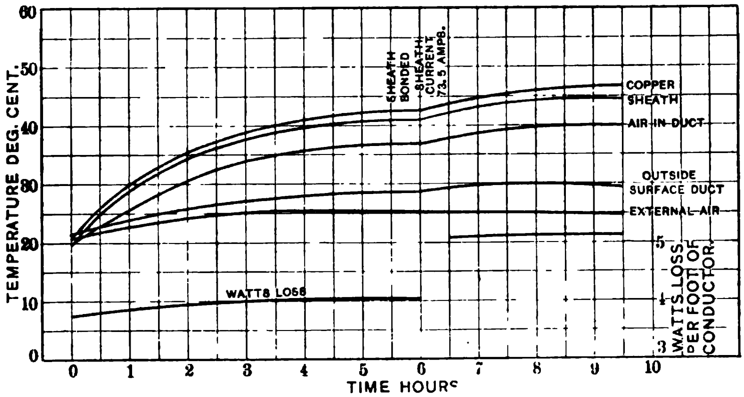

FIG. 27—TEMPERATURE OF 1,000,000-CIR. MIL CABLE.
13/64 in. rubber, 3/32 in. lead. In conduit, at 600 amperes. Test No. 12.

Cables heavily loaded should not be placed in the top ducts, as there is a natural tendency for the rising heat of the entire system to elevate the temperature of these ducts above the rest.

By referring to Fig. 24 it will be found that 2.5 watts loss per foot corresponds to about 475 amperes load on the 1,000,000-cir. mil cables, and four watts loss per foot to about 600 amperes.

In order to operate the line at these values of loss, it is not only necessary to locate the cables properly with regard to their loads, but also to arrange the cables so that there is little or no possibility of their coming in contact in the manholes. An accidental contact between the lead sheaths will result in puncture of the sheaths if they are bonded or in contact with each other at some other point.

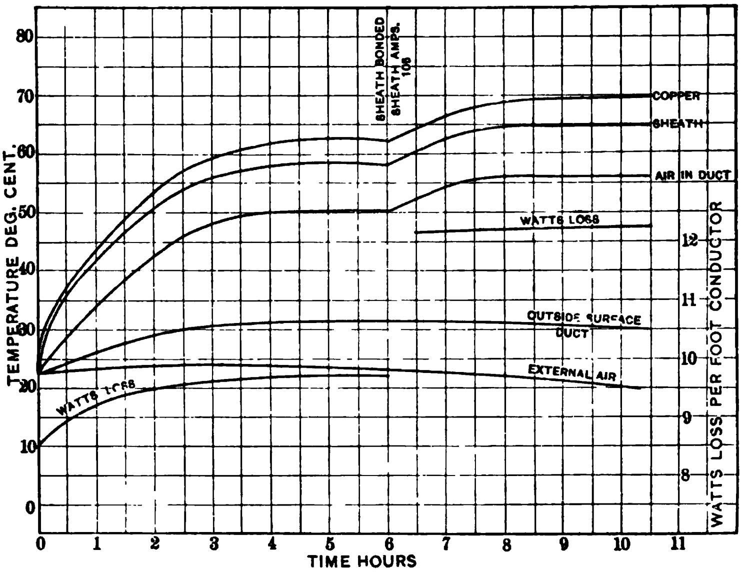

FIG. 28—TEMPERATURE OF 1,000,000-CIR. MIL CABLE.
13/64 in. rubber, 3/32 in. lead. In conduit, at 900 amperes. Test No. 12.

The passage of the alternating current through the conductor induces an e.m.f. in the cable sheath and unless the sheaths are grounded the sheath of a long length of cable may be at a moderate potential above earth. Possibly the wisest procedure would be to bond together all cables of the same phase at one point and ground them there through a resistance.

Where single-conductor lead-covered cables carrying alternating current are supported in manholes on iron brackets, the sheaths may be insulated from the bracket by split rubber lined hose.

During heavy short-circuits in the system, however, the cables carrying the short-circuit current may be thrown from their supports by the magnetic repulsion or attraction due to large currents. This forms a strong argument in favor of wrapping all cables in manholes with asbestos tape, afterwards treated with silicate of soda, and the use of fibre duct, thus insulating against the sheath voltages.

The lead sheaths of cables carrying high-potential currents should always be grounded at some one point.

DISCUSSION ON "NOTES ON UNDERGROUND CONDUITS AND CABLES" (MOSMAN), BOSTON, MASS., MAY 15, 1912.

A. E. Kennelly: This paper manifestly embodies a large amount of valuable experimental work. It is work, as has been stated, done under very trying conditions, and we are all the more indebted to those who have done the work on that account. We have, it is true, known but little concerning the heating conditions inside ducts, although we know fairly well the heating conditions around a single cable of known dimensions buried at a given depth in the ordinary soil. I do not mean to say that we ought to be content with the knowledge which we have in that direction, but at least we have some knowledge.

The data obtained are interesting. This underground system, as shown in Fig. 1, was largely an "over-ground" system. Nevertheless, there is one section that does seem to have been truly an underground system, although just how deep underground I have not seen it stated. I think it would be important if some measurement could be given of that depth. The data led to the showing, as Mr. Mosman has said, of what this particular conduit will stand without overheating the cables it contains; and in a general way, of course, what is true of a duct in the conditions here might be acceptable in general. But it is very important, it seems to me, that the data collected here at so much time and expense should be made available for general purposes, besides being applicable to this specific case and this particular number of ducts; and I think the measurements made here are applicable to such a generalisation.

If we take a conductor that is cylindrical and suppose it to be buried in water so as to keep its temperature at the surface down to a known amount, and then send a uniform current density all through the cable—which of course would not be possible with a large conductor and alternating current—the hottest place would be in the center and the temperature gradient would be lowest, naturally, at the very outside or the skin. That has been worked out. In a cable of 1,000,000 cir. mils the difference of temperature at the center and at the skin is a small fraction of a deg. cent., with ordinary loading, so that with copper the difference of temperature that one would get is quite negligible from an engineering standpoint; but if we take a large cylinder of very poor thermal conducting material and moderately good electrical conducting material, the difference of temperature that we can get between the center and the surface is very material; and large conduits, if they were made circular and then filled up like the cross-section of a watertube boiler, might be considered as having moderate electric conductance, together with a very considerable thermal resistance. This is made up of the cement and the fibre, modified by the presence of the cables. Electric conductance is supplied by the cables themselves. The way such a test would naturally be made is in the manner recorded here. Of course it assumes a circular conduit. We do not get them circular—we get them square. That makes the computation very hard instead of comparatively simple. Nevertheless, if we take a square conduit, as in this case, and make the equivalent circle, I do not like to say what the error would be, but I do not think it would be very great and the computation would be approximate for engineering purposes. So that this gives us data from which we can get the average thermal conductance per foot, provided the duct surface has a known temperature. If it has the same temperature all the way round and it is known, then, knowing the temperature at any distance from the center, we can compute that and apply it to any duct for which the temperature on the outside can be specified. That has to be done, of course, not only for a duct of cement or fibre, but for a duct of other materials; on one where the relative dimensions of the tube differ. It would only be necessary, probably, to make similar tests upon a few feet of duct of different materials.

One very interesting thing brought out is that the ends make such a tremendous difference. That is surprising to me and I should not have supposed that the drop of temperature at the ends of the duct would be anything like as great as shown by the curve in Fig. 15. You can see the gradients starting at the middle. This shows how much heat may be carried out of a duct with stationary air by thermal conduction—apparently through the sheath—and how carefully the measurements should be made to avoid that effect in making such tests as these I am speaking of and as are detailed in connection with Figs. 16 and 17. An inference drawn from the paper is that one can, by means of forced draft, make a duct workable that would be unworkable otherwise.

The above result is very useful, but I think it would be a very expensive method to maintain except under good local conditions. It seems to me that the next best arrangement would be to make a hollow conduit, that is, if we have a square conduit we could build it up at the sides, and leave the interior part hollow. But in all cases it should be put down underground. A hole in the ground is much cooler than a hole in the air, for any duct or cable. One would naturally suppose that a duct which was surrounded on all sides by air would be kept cooler than a duct buried in the ground, especially in the winter time, but I think all theory and practical evidence is against that being true. It is best to have a conduit underground. Of course I am speaking of a hollow conduit. If you are going to have a conduit full, you would put the lightly loaded members in the center and protect them by the more heavily loaded members, so that the temperature might be very flat in the center owing to the small amount of current. The data given in Figs. 16 and 17 seem to me to be excellent for the purpose of determining the average thermal resistance, on the assumption that the conduit is of square cross-section.

L. L. Elden: As Mr. Mosman has stated, the installation of conduit and cables which has been described in his paper does not represent commercial conditions usually present in central station systems. It should further be noted that the author's conclusions with regard to carrying capacity of cables are not applicable to central station operations.

Experience in conduit constructions indicates that it is inadvisable to install more than 12 to 16 ducts in any single group entering a manhole, with a strong preference for the smaller number in city construction. With moderate size conduit lines it becomes possible to protect cables from injury due to burn-outs which may occur from time to time, more effectually than is possible in manholes where a large number of cables are concentrated.

When considering the carrying capacities of different classes of cables, recognition should be given the seasonal changes and climatic conditions governing temperatures in each part of the country under consideration. In this particular latitude, central station operations have to contend with maximum load periods averaging approximately one hour, therefore it is possible to apply more liberal ratings to cables or other apparatus used in such service than would be the case in localities where higher temperatures are normally experienced.

If we consider the ordinary city conduit, it will be found that, owing to the variety in size and types of cable ordinarily used, the radiation of heat from heavily loaded cables is materially assisted, or at any rate not impeded, by the other cables in the same conduit, many of which do not suffer any rise in temperature from their own currents owing to their small values.

In enumerating these cables, low-tension a-c. and d-c. feeders and transmission lines are those which suffer the largest temperature rises, and, therefore, need to be placed in the most favorable positions to effect easy radiation, while cables used for primaries, low-tension a-c. or d-c. mains, neutrals, pressure wires and series arc lighting circuits rarely need to be considered as far as radiation of internal heat is concerned, thereby permitting their installation in such locations in conduits as may be convenient.

When placing cables in conduits, it is advisable to place heavily loaded cables in the outside ducts along the sides and at the top of conduits, leaving the smaller and cooler cables to occupy the bottom and central positions.

Referring to commercial practise in the design of conduits, it usually is unnecessary to make elaborate calculations on the radiation of heat from cables in conduits of medium size, for the reasons above stated. However, at station exits where large numbers of cables are necessarily grouped together, care should be exercised to provide properly for any excess temperatures which may be developed, particularly in large direct-current distribution systems. The dissipation of energy per duct-foot which the author has suggested as being allowable is many times exceeded in regular service on short hour peaks, in fact four times the limit referred to by Mr. Mosman is regularly attained in certain locations without detriment to the cable. After looking through a number of temperature readings taken on cables in the Boston Edison system in the past, it seemed advisable to obtain some additional records of similar character today, and these are presented as of possible interest.

1. Manhole at entrance to substation connecting with a 12-duct conduit. Six 1,000,000-cir. mil d-c. cables in conduit.
Cable tested after carrying 700 amperes six hours.
Manhole temperature, 22 deg. cent.; cable temperature, 43 deg. cent.; rise, 21 deg. cent.

2. Manhole in street connecting a 4-duct conduit. One 1,000,000-cir. mil cable in conduit.
Cable tested after carrying 800 amperes four hours.
Manhole temperature, 18 deg. cent.; cable temperature, 38 deg. cent.; rise, 20 deg. cent.

3. Manhole in street connecting a 24-duct conduit. Six 4/0 three-conductor transmission cables and miscellaneous cables in conduit.
One 4/0 three-conductor cable tested after carrying 210 amperes 8 hours.
Manhole temperature, 15 deg. cent.; cable temperature, 27 deg. cent.; rise, 12 deg. cent.

4. Manhole in street connecting a 9-duct conduit. One 1/0 three-conductor transmission cable and miscellaneous series arc cables in conduit.

One 1/0 three-conductor transmission cable tested after five hours' run at 100 amperes.
Manhole temperature, 15 deg. cent.; cable temperature, 20 deg. cent.; rise, 5 deg. cent.

5. Temperatures taken at end of conduit inside a station building.
Room temperature, 21 deg. cent.; cable temperature (average), 35 deg. cent.; rise, 14 deg. cent.

6. Tests in large conduit leaving the substation in this particular building in a conduit line consisting of 45 ducts, each occupied by one 1,000,000-cir. mil d-c. cable. Total current leaving the station, 7000 amperes.
Manhole temperature, 20 deg. cent. Tests on various cables after carrying the following specified loads four to six hours:
1,000,000-cir. mil d-c. cable, 500 amperes, 23 deg. cent., rise 3 deg. cent.
" " " " " 700 " 30 " " " 7 " "
" " " " " 200 " 21½ " " " 1½ " "

Variations in temperature were noted among cables carrying the same loads, due to their location in the conduit with reference to the loaded cables, and to the outside faces of conduit.

7. Temperature of a 1,000,000-cir. mil d-c. cable carrying 800 amperes for a long period, in location not affected by other cable, showed a rise of 40 deg. cent.

8. Temperature of 1,000,000-cir. mil concentric cable used for d-c.

feeders and operated at 1000 amperes showed approximately the following increase in temperature:

	1st hour temperature rise	2nd hour temperature rise	3rd hour temperature rise
Sheath..........	10 deg. cent.	25 deg. cent.	40 deg. cent.
Outer conductor...	20 " "	40 " "	55 " "
Inner conductor..	21 " "	42 " "	60 " "

While this type of cable is not as well adapted for continuous heavy duty as are single-conductor cables, the economies which it effects in duct space and its ability to carry heavy loads from two to three hours make it eminently satisfactory for central station systems.

9. Temperature of 4/0 three-conductor 15,000-volt cable operated at 250 amperes attained a rise of 47 deg. cent. after two hours, and at 300 amperes a rise of 63 deg. cent.

These tests were made on individual cables in conduits with other cables and indicate the average conditions which would obtain in the ordinary operations of the system.

In connection with these tests it has been demonstrated that the winter temperatures in manholes closely approximate 10 deg. cent., while summer temperatures reach 25 deg. cent., a condition particularly favorable in connection with the operation of a cable system under maximum load conditions as they occur in this latitude.

From every point of view the method of designating the carrying capacity of cables by temperature rise is misleading in effect, as full value or use of cables cannot be attained by such methods. It is contended that a determination of the maximum allowable cable temperature should be the true method of rating a cable, thereby leaving it possible for the operators of distributing systems to work cables at higher kw. capacities in winter than in summer. For instance, repeated tests on 1,000,000-cir. mil and three-conductor cables as between winter and summer conditions show that the winter ratings may properly exceed the summer ratings of such cables by 10 to 15 per cent while attaining the same maximum temperature.

The suggestion is made by the author that a 50 deg. cent. rise is good practise for paper-insulated cable for high-tension work. Assuming that this rise is to be calculated for a base of 20 deg. cent., a maximum temperature of 70 deg. cent. would result, as compared with 73 deg. cent. in English and European practise. As the average temperature in England is lower than in Massachusetts, the advantage of the maximum temperature method of rating is obvious.

Referring to foreign cables, it should be noted that the impregnating compounds used abroad are somewhat different in composition from those with which we are familiar, in that they are adapted for operation at higher temperatures.

Mr. Mosman has spoken of bonding methods and troubles resulting from sheath currents. With 1,000,000-cir. mil lead-covered cables used for alternating-current service, sheath currents are developed which require serious attention, although such installations are rarely met with in commercial service, for obvious reasons.

Primary or secondary a-c. mains using single-conductor cables larger than 350,000 cir. mils are rarely met with in central station systems, and owing to the distances covered, it rarely occurs that such cables are loaded to exceed two-thirds their maximum carrying capacity, under which conditions the sheath currents do not exceed 10 per cent of the line current, an amount of current easily cared for by proper bonding. Wherever possible this evil may be avoided by using multiple-conductor cables for a-c. distribution.

Bonding of cable systems should receive serious attention by all operating companies, first to avoid damage to cable sheath from electrolysis, and secondly to avoid sparking between sheaths.

Good practise indicates that all cables in manholes should be substantially bonded together and grounded at frequent intervals, and in some cases special conditions may indicate the desirability of bonding to railway return systems to avoid electrolytic troubles.

In transmission systems operating with a grounded neutral, it is particularly desirable that all transmission cables be securely bonded together and in some locations securely grounded in order to insure a path of low resistance for fault currents in the event of cable failures.

The lack of definite knowledge of the relative radiating values of the different forms of ducts, when installed in groups of various shapes and sizes, and in different soils at varying depths, under conditions regularly met with in practise, is regrettable, and studies on this subject would be of great value.

The radiating value of fibre duct is practically an unknown factor, although its advantages in other directions are well known, particularly in the assistance it affords in insulating cable sheaths from ground currents in locations where conditions are favorable and where such construction affords relief from electrolysis.

William L. Puffer: Referring to Dr. Kennelly's idea of hollow construction, I believe that the proper way of considering this whole matter is to take into consideration what lies outside the surface of the conduit. The heat is carried away by the earth. You have a certain circumference of the duct line going through the earth. The question is, how fast the earth can take heat away from that. Consider everything inside the conduit line as a sort of composite device which is producing heat. Note Fig. 17, bearing in mind that the direction spoken of is diagonal, not horizontal or longitudinal to the surface of the conduit. If you will notice the numbering on these ducts, you will see that these are given diagonally and not from duct to duct measured from the outside inward. Also note that it would be better if you drew a horizontal reference line at about the figure 20, in Fig. 17, representing the temperature of the earth, which has been referred to as about 20 deg. cent. You will notice then that your curve has a different appearance as you get inside the duct line, the temperature rising enormously. In Fig. 18, if you will draw that horizontal line through the 20-deg. mark you will notice that the first curve, for duct No. 1, shows a comparatively small rise in temperature. Then as you go diagonally into that duct line the temperature is rising enormously.

Referring to the remarks on the next to the last page, concerning the data given in Fig. 24, the copper carrying capacity is interesting. A loss of 2.5 watts per foot (30.5 cm.) or 475 amperes on the 1,000,000-cir. mil cable corresponds to 2100 mils per ampere or about 600 amperes per sq. in. (6.45 sq. cm.), which you see is comparatively low density. Then the four watts per ft. corresponds to about 1700 cir. mils per ampere or a density of approximately 775 amperes to the sq. in. (6.45 sq. cm.). If you will turn to Figs. 25, 26 and 27 and notice the way in which these temperature rises are made up, beginning at the top at the extreme right of the curves, you will notice that there is very little temperature difference between the copper and the sheath—something like three or four degrees. That compares very well with measurements which I have taken by a very refined method, where there is no room for query. The data are unusually correct for a duct line in service. There is a big difference between the temperatures of the sheath and the air in the duct. I think that is due to the method of measurement. If there is any way of producing artificial cooling so that you can eliminate a large part of the difference in temperature between the sheath and the outside air or ground, there will be a chance to spend money to great advantage. I have suggested, and this suggestion I do not claim is original, that the way to do with a line that is going to run a great deal of current for a long time is to see that the ducts are full of water. If you ever try heating water you will find that it takes a great many watts per foot before you can raise the temperature, and if you put water through these ducts you will find that the carrying capacity will go up enormously. That same idea is possible in measurements. I imagine that the temperature measurements were made up from the resistance of iron wire which had been calibrated externally, then pulled into the ducts and the drop measured. You will notice that would give two readings, because of the fact that the wire is cooled by the external body of the duct in which it is resting, so you would get a lower indication than you would have if the wire were in position during the calibration, so that these temperatures, I think, should be even higher. I think the results have been understated rather than overstated, due to that possible error.

If you will look up Fig. 8 and observe the carrying capacity of the different ducts making up this 9 by 9 line, you will realize that substantially 40 per cent of the ducts are not loaded anywhere near their capacity, so that the figures we read in here really have to do with a duct line which has only three tubes, being cooled on one side by a temperature which is comparatively low, 36 to 22 deg. cent., and on the other side a temperature of something like 25 or 26 deg. cent. So the information in this part of the paper should not be confused with that which is given a little later on. I think that it would have been well to include a sketch showing the temperatures in the duct which was actually underground.

I do not see anything to criticise unfavorably in the paper, and I know very well from experience how hard it is to make any sort of tests that will plot anywhere near a straight or curved line under such conditions as those under which this has to be done; and the fact that the investigators got any curve line at all shows to my mind that they should receive a great deal of credit for doing this work.

William Clark: In reference to Professor Puffer's statement, regarding the calibration of the test wires, the sample of wire was wound on a spool and immersed in oil contained in a tank which was also immersed in water, the temperature of which could be controlled, so that we had a direct contact with the cooling medium as nearly as possible approximating the result obtained in the duct, although in the duct there was but a small contact between the iron wire and the fibre.

In reply to Dr. Kennelly's question concerning the earth's surface and the top of the conduit line, no measurements were made, but it is my impression that the concrete envelope was 18 in. or 2 ft. (45 to 60 cm.) below the surface of the earth.

E. N. Lake: These experiments show rather conclusively the influence of thermal conductance and radiating surfaces upon temperature rises. In this connection, I think it will be granted that a clay material has a better conductance than the fibrous material. The square duct, as has been suggested by one of the previous speakers, has a larger radiating surface. That also gives a slightly larger surrounding medium of air. So I believe the question of the relative advantages of round fibre duct as against square clay duct is worthy of very careful consideration and a good deal of study on the part of distribution engineers. There are a number of large systems in this country that have, after a considerable amount of experimentation, adopted the single, square, clay duct.

In the matter of manhole protection to cables, several companies have used a little different method from that suggested by Mr. Mosman, and that is, to support the cables in the manholes not upon metal racks but upon some form of shelving, and to protect them one from the other, so as to isolate the cables in the case of burn-outs, by the same class of material that is used throughout the length of the duct, namely, vitrified clay, using for this purpose split sections.

Fig. 15 shows very strikingly the relation of radiation and conductance. I would like to suggest that perhaps the temperatures as given by Mr. Elden were temperatures that would correspond to the temperature conditions of cables at the manholes.

As to the matter of conduit construction, a subdivision of duct line is usually, although not always, possible—a construction which carries through the center of the duct section a dividing wall of the conduit. This has been used to very good advantage—a construction which has been called duplex construction—using a maximum single section of 12 or 16 ducts, but a total section of 24 or 32, carrying the opposite section in the other side of the manhole. This has been done primarily to accomplish, as nearly as possible, perfect separation of the cables, so that trouble in one conductor will not be transmitted to the entire group in one manhole.

One of the preceding speakers mentioned the use of water as a medium for surrounding the cables. I recall a case of serious trouble that at the time, without giving very much thought to it, we attributed to the presence of water in the ducts and manholes. There were some forty-two 600-volt railway cables in a conduit line filled with water, covering the entire number of cables. What is called by distribution men a " slow burn-out " occurred. It was so slow that the men could keep the circuit breakers in at the station, working at it industriously. After a couple of hours of this kind of operation, between one and three o'clock in the morning, it was discovered that all 42 of these cables were burned off under the water. I do not know whether it would be possible for that to occur under any other conditions or not, but it was one of the most unusual burn-outs that has ever come to my attention.

G. A. Burnham: I can perhaps answer the question Dr. Kennelly brought up about Fig. 15. If you compare Fig. 15 with Fig. 12 you will note that the variation in temperature in both curves, that is, the difference between the minimum of one curve and the maximum of the same curve, is practically the same; it is approximately 25 deg. cent. between the low point and the high point. The reason for the curve in Fig. 15 dropping off so abruptly on the right-hand side is that that manhole, if I remember correctly, was open to the air on one side. The temperature in manhole No. 9, I think, was considerably lower than manhole No. 4. Now in curve No. 12 of manholes 3 and 4, we had a 10-in. (25-cm.) vent pipe in No. 4, and the temperature was very much higher than in No. 3, due to direction of air current. I think the temperatures which Mr. Elden mentioned were at the mouths of the manholes. Although his temperatures are rather low, they seem to bear out the conclusions which have been arrived at in this paper, that the temperatures within the duct are considerably higher than is indicated at the mouth of the manhole, because it does not appear that there can be a great deal of circulation and natural ventilation in a long conduit line; that seems to be practically proved by Fig. 15. That shows practically no ventilation, no action of air from one end to the other, as a contrast to Fig. 12. In Fig. 12 the direction of air is from right to left, from manhole No. 3 to manhole No. 4, because the air sweeping down through the ducts carries the heat with it.

Curve 1 in Fig. 23 seems to indicate that the contact resistance and resistance of the ammeter coil was practically 60 per cent of the total resistance of the lead sheath.

That same ammeter, with the same method of bonding, was applied to the spinning room circuits, and those were approximately 275 ft. (84 m.), and one would naturally expect that curve 2 of Fig. 23, showing the sheath currents in the spinning room circuit, would be much higher than it is, because the resistance per foot of the lead sheath, including the contact resistance of the bonds and the resistance of the ammeter coil, would be considerably higher than would be the case in the experimental cable, and with the same current density there would be the same flux and induced voltage per foot. So one would expect that curve 2 would be a great deal higher than shown, if the readings on curve 1 are correct.

The point brought up by Professor Puffer, about the measurements of the temperatures not being taken in a horizontal direction, is interesting. Of the two curves which are plotted in Fig. 17, one is a curve starting at the upper left-hand corner of the conduit line and running at an angle of 45 deg. downward, and the other is starting at the left-hand bottom corner of the conduit and running 45 deg. upward, and the two curves practically coincide, so it seems to me that is a fairly average condition.

David Harrington: I wish to discuss the practical side of the question—what we are going to do about it. There does not seem to be much doubt that there is a certain amount of heating through the ducts, and it seems very natural that there should be, under the circumstances. I am somewhat skeptical in regard to Dr. Kennelly's idea of a central duct. I should be rather doubtful about the efficacy of a duct filled with still air doing much in the way of conducting away the heat. I think it is doubtful whether still material of that kind, either air or water, would for any considerable time take care of the heat; but I do believe that the day is coming and is perhaps nearer than we think, when the central station man can control the conditions in the manholes and in the conduits.

People have fought rather shy of this question. When a pole line needs anything done to it or there is any difficulty, they get after it and find out what is the matter with it, and from time to time they inspect the system; and also the engine is oiled, nowadays, so that it will run properly; but an underground conduit is put into the ground, the manhole is built, and they say " Let it go and it will take care of itself." I do not believe that attitude is going to be mantained for a great length of time, and I believe we can control the conditions of the manhole and of the ducts. Without going into details, I believe that with a forced draft the air could be controlled at practically whatever temperature may be desired, and perhaps at an expense which would be thoroughly warranted by the saving received. Moreover, the advantage of controlling the manholes and ducts by a draft of air would entirely take away the problem which we have from gas in our manholes. That would be taken care of at the same time as the temperature. I doubt if there is very much difference for a long space of time in the temperature of the ground immediately outside the duct. I think that under ordinary conditions the ground immediately adjacent to the ducts becomes of the same temperature as the ducts and is somewhat slow in dissipating the heat. I think we could get a very much quicker and more satisfactory regulation by moving air than we would by the still earth, still water or air. This method I do not think is so difficult as people believe. In the first place, the large conduits which would naturally be most affected by the heat are in general rather close to the station and they would be more easily reached than a smaller duct, which would not need ventilation so much, perhaps. Some twenty years ago in New York the condition of the conduits was regulated by air pressure from the station, and that was at a considerable distance from the station. It was found not be be an expensive or a difficult thing to do, and a very simple method of maintaining air pressure was found efficacious. Of course the parts of the transmission lines which would naturally carry the heavy current are generally in small conduits and probably would not be as much affected as the larger conduits. It is my opinion that possibly attending to the condition of the conduits and the air in them, and regulating that, might be a simpler matter than to try to regulate the cables and adapt them to the conditions which we find in the conduits.

George W. Palmer, Jr.: This paper shows that there has been a great deal of care taken in getting it into shape. There is very little literature extant on the subject of the limitation of the carrying capacity of cables due to the manner in which the heat is radiated from the cables, and any contribution to this subject is to be welcomed.

It is evident that operating companies which are now using or have been using overhead conductors, and have been accustomed to overload them heavily, have got to modify their practise very materially when they come to put the conductors into underground conduits. Now we are not going to be able to work these conductors at the same current density when we get them underground. I would have been glad to see some data given in the paper on the performance of cables in tile duct, which has been longer and more extensively in use than the fibre duct, which has come into use within the last few years.

I think it is evident from what has been said that something can be accomplished where a conduit has a large number of ducts, in making it of the shape, so far as may be, to give the most favorable radiation. I note that resistance to puncture as given by the author does not decrease for paper as rapidly as it does for cambric, and that is interesting.

We have tried to keep our conduits dry. If water gets into a manhole, we drain it, and we lay our ducts always with such a pitch that there will be no water left in them. I should hesitate for a long time before filling up the ducts with water. We know that the presence of water increases certain troubles in our cable sheaths and makes them much more likely to fail. I am somewhat surprised to see the values which are given for sheath currents. I note that on 1,000,000-cir. mil cable carrying 500 amperes the author gives 175 amperes. This is somewhat larger than I should have supposed the value to be. The safe carrying capacity, the author evidently thinks, from the conclusions he draws from his data, is 2.5 watts loss per foot (30.5 cm.) of duct, corresponding to a load of 475 amperes on a 1,000,000-cir. mil cable. It seems to me that if we are not going to be able to work our cables at any higher current density than that, we must find some cheaper metal than copper to use. At the end of the paper the author comments about these sheath currents, which raises the question of whether or not it is more desirable that all the phases of the circuit should be included in one cable. We found in our own practise a number of cases where electrolysis occurred in single-conductor a-c. cable with lead sheath. As the cable happened to belong to somebody else and was laid somewhere near a street railway track, the railway company was immediately accused of damaging the cable, but I think the company was able to convince the owners of the cable that the cause was elsewhere. In regard to the protection of the cable in the manholes with silicate of soda, while we have never used that, I understand it is of no value where there is dampness present in manholes.

William L. Puffer: This paper, we must remember, treats of a 9 by 9 duct conduit, run with alternating current, presumably entirely ungrounded. Two of those who have taken part in the discussion have compared with it certain systems which every one thinks at times are grounded, and the comparison is not a fair one. The question of the presence of water in ducts and manholes also is not fairly compared with what might happen here, for the same reason, that they are operating with grounded systems, and practically selecting the ground as the other wire. In this test the return wire is in the line and no part of it would be grounded, and moreover, it is alternating current, and the results will naturally be very different.

L. L. Elden: I do not know whether or not the gas problem which is encountered in city practise is appreciated, but at any rate it has become necessary in Boston to ventilate the manholes, and I am at a loss to know how it would be possible to maintain air pressure with a 4-in. (10-cm.) opening in every manhole, beginning with the first one from the station. I believe such a system means a closed manhole system with many points provided for the supply of air, and provision must be made to avoid the collection of gas in pockets or dead-ended conduits. I believe this scheme was abandoned in New York for the reason that the conditions became prohibitive for its operation. Professor Puffer has spoken about water in conduit systems. There is no question that at times it is a convenience to have in some systems, providing suitable means are available to remove it quickly when necessary.

David Harrington: In regard to the matter of regulation of air pressure, I would recommend a system of air circulation which was regulated through an underground system. I would not expect to turn air loose in a system and let it take care of itself.

I think people do not appreciate how comparatively easy it is to ventilate and maintain a proper temperature through a very considerable length of conduit. Personally, I never have been a great believer in ventilated manhole covers as a method of ventilation for a system. There are two or three things about it which I think are bad. In the first place the system does not stay open because most of the holes get plugged up, and then if it does stay open, in my experience, it does not ventilate the manhole. But I would recommend an absolute system of ventilation through manholes and of cooling through manholes, and I believe it can be done without regard to the manhole covers. I would say this, however, that in order to make an efficacious system for ventilating and cooling the ducts, the ducts must be tight. That is the case with any method; whether you are going to cool by air or water or something else, you must have a tight duct.

L. L. Elden: Another word in regard to ventilating manhole covers. A simple test at the perforations in such covers readily shows that as a means for establishing a circulation of air within the conduits, this method of ventilation is reasonably efficient. In practise it has been noted that where double or otherwise tight manhole covers are employed, explosions are much more destructive than where perforated covers are used. In the first case, the street surface is usually severely affected, while in the latter only the cover is dislodged.

Philip Torchio: Mr. Mosman gives the results of heating of cables in ducts for a subway structure consisting of 81 ducts. Modern practise is against the adoption of a large number of ducts in one trench, as it has been found that it is not economical to practically halve the carrying capacity of the cables to save a few cents in conduit construction.

A very important subject brought up by Mr. Mosman is the effect of alternating currents on single-conductor leaded cables.

The New York Edison Company has on several occasions carried out tests along the lines followed by Mr. Mosman, and I present herewith two reports, one of January, 1907, and one of April, 1912, which may pertinently supplement Mr. Mosman's results, as they were carried out for frequencies of 25 and 60 cycles, instead of the frequency of 40 cycles dealt with in the author's paper.

I think that all of this information is valuable to central station engineers, as information of this character is rather meager. As to some conclusions of Mr. Mosman, I am not prepared either to endorse them or to take issue with them. I want, however, to point out that there may be disadvantages in relying on the maintenance of insulation in ducts and manholes for a long single-conductor leaded cable carrying large alternating currents. A safer procedure would probably be the frequent bonding and grounding of the lead sheaths so as to reduce the amperes flowing in any one length to a moderate amount.

For low-tension work, however, as for instance in the case described in the paper, I would consider the use of concentric or multi-conductor cables preferable to the single-conductor cables. Where single-conductor cables must be used, some form of waterproof insulation and braiding could be used to advantage for voltages not exceeding 2000. For higher voltages, braided cables must be, in addition, supported by highly insulating clamps to prevent their destruction from static discharges to neighboring high-resistance grounds.

Induced Currents in Cable Sheaths—January, 1907. The following tests were made to measure the currents induced in the lead sheaths of the cables on generator No. 10 in Waterside Station No. 2.

Length of cables	106 ft. (32.3 m.)
Outside diameter	2⅜ in. (60.3 mm.)
Thickness of lead	⅛ in. (3.175 mm.)
Copper	1,500,000 cir. mils
Cross-section of lead	0.8835 sq. in. (5679.7 sq. mm.)
Resistance of lead	0.000105 ohms per ft. (304.8 mm.)

When tested, these cable sheaths were permanently bonded and grounded at the upper end in the transformer gallery. All other bonds and grounds were cleared, down to the generator terminals, where the bond wires were opened for measurements. Under these conditions the sheath circuits were star-connected, and it was found that the open-circuit voltage from end to end on one sheath was 1.38 volts, with 360 primary amperes. Reading across the open ends of two legs, 2.56 volts was observed, against a calculated voltage of 2.39, assuming the two to have a phase difference of 120 deg. ($\sqrt{3} \times 1.38$).

Upon completing the circuit by joining the generator end to a common connection through an ammeter, the voltage from end to end dropped to 1.10 volts, the current flowing along the sheath being 15 amperes.

With 632 amperes, a current of 44 amperes was measured, flowing from the sheath to the common connection.

A test for unbalanced current to ground was made by observing the current in the three leads from the sheaths to the common connection, and also the current flowing from the common connection to ground.

With 360 primary amperes, the currents flowing along the three sheaths were about 18 amperes, while the current to ground was 0.35 ampere. As the ammeters and connections were not all of the same resistance, this probably accounts for the unbalanced current.

A bond was made in the basement about 35 ft. (10.6 m.) from the generator and tying the three sheaths together; under these conditions the current at the generator end was reduced from 26 amperes without the bond, to 12 amperes with the bond, with 450 primary amperes.

In general, therefore, it appears that the currents induced in the sheaths are balanced, or nearly so, and that if the bonds between the sheaths are heavy enough, and make good contact, there will be practically no current to ground. In order to reduce the current flowing in any bond wire, several bonds should be provided.

For the No. 10 generator cables at Waterside Station No. 2, it appears that with 25 cycles, 800 primary amperes, bonds about every 40 ft. (12.2 m.) should not have more than about 18 amperes flowing in them. It would seem to be sufficient to ground the bonds at the ends of the cable, if the bond connections are all made with good contacts.

Induced Currents in Lead Cable Sheaths—April 30, 1912. The following tests were made to measure the currents induced in the lead sheath of a 1,500,000-cir. mil single-conductor cable. The tests were made in comparison with a similar cable with braid covering.

The two sample cables were drawn into tile ducts, both in outside ducts and separated from each other by an empty duct; this location placed them 14 in. (356 mm.) apart between centers. The two cables were connected together at one end, and current was passed through them in series. The two ends of the lead sheath were connected together through a 500,000-cir. mil cable. Complete measurements were made in the main circuit for both the lead and braid-covered cables, and also in the sheath circuit. The ducts were broken away at a point about midway from the ends, in order that temperatures might be observed at this point.

The detailed dimensions of the samples were as follows:

Lead-covered cable: 1,500,000 cir. mils; conductor diameter 1.625 in. (41.3 mm.); sheath diameter, inner, 2.125 in. (54 mm.), outer 2.375 in.

(60.3 mm.); 190.1 ft. (57.94 m.) long. Braid-covered cable: 1,500,000 cir. mils; 191.5 ft. (58.37 m.) long.

Resistance at 23 deg. cent.

Conductor of lead-covered cable = 7.58 × 10^{-6} ohms per ft. (304.8 mm.)
" " braid- " " = 7.43 × 10^{-6} " " "
Lead sheath = 117. × 10^{-6} " " "

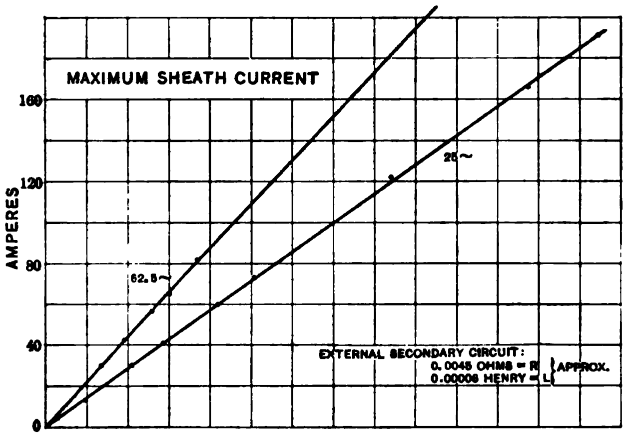

FIG. 1

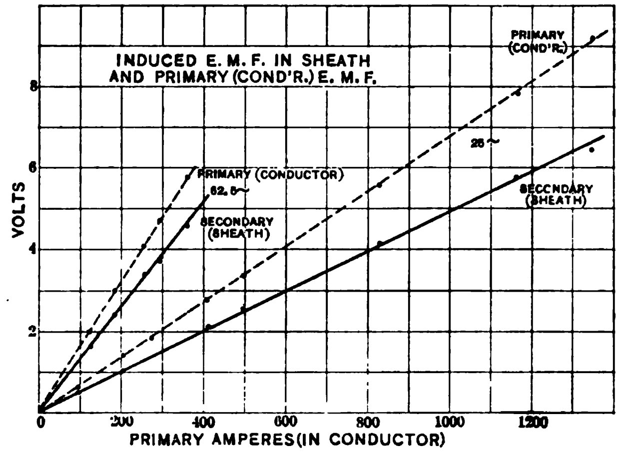

FIG. 2

Measurements were made of induced volts in the sheath, current flowing in the sheath circuit when connected through an external conductor, and losses, and the results are shown in the accompanying curves, Figs. 1 to 7. The currents measured are probably maximum currents, or as high as may be expected in practise, as the connections and external circuit were all of low resistance.

Fig. 2 shows the e.m.f. induced in the sheath, together with the impressed voltage on the conductor as primary volts. Fig. 1 shows the current flowing in the sheath and external circuit, when the ends of the sheath are joined.

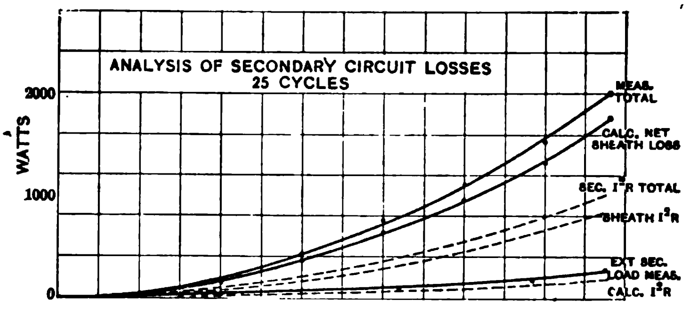

FIG. 3

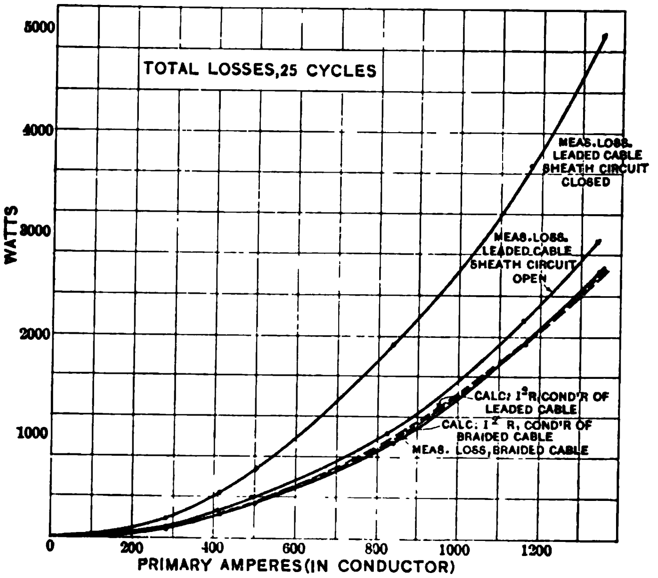

FIG. 4

Fig. 4 shows the measured and calculated losses in the leaded and braided cables at 25 cycles. Comparison with the calculated I^2R loss shows close agreement for the braid cable, within the accuracy of the measurements; the leaded cable, however, shows a materially greater loss than accounted for by calculated I^2R

with the sheath circuit open; this difference is apparently due to eddy currents in the sheath.

Fig. 3 is an analysis of the secondary circuit losses at 25 cycles, that is, both the losses in the sheath itself and the losses in the conductor connecting the ends of the sheath, considering the sheath as a transformer secondary and the connection as an external load upon this secondary. It will be seen that the measured power in the external load agrees fairly with the calculated I^2R, probably within the accuracy of the measurements; the net loss in the sheath, however, is nearly twice the calculated I^2R. It was not possible, with the available facilities, further to analyze this loss, and we are unable to state whether it is due to increased eddy currents, or not.

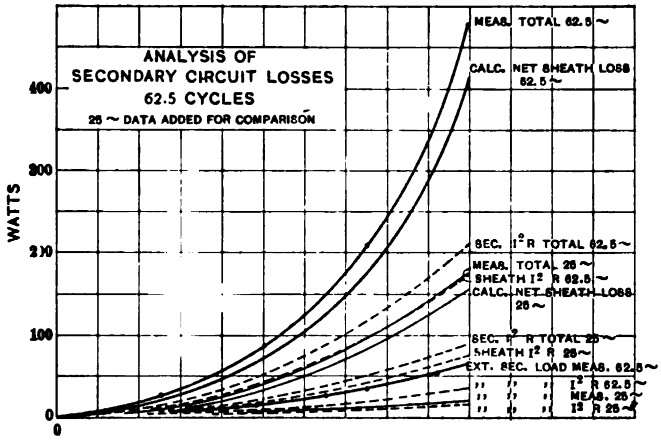

Fig. 5

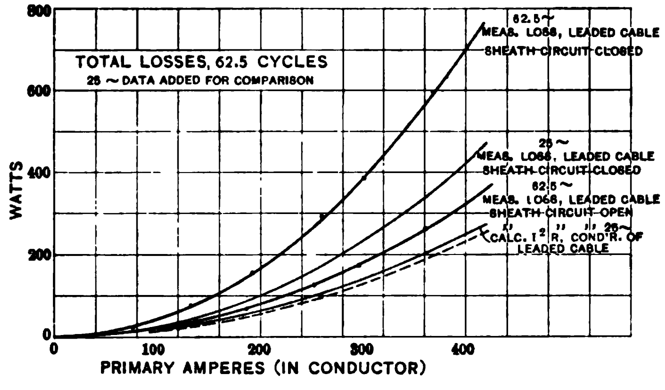

Fig. 6

Fig. 6 shows the measured and calculated losses in the leaded and braided cables at 62.5 cycles. As in the 25-cycle test, the loss in the braided cable is substantially the same as the I^2R, while the leaded cable shows an excess over I^2R, more marked than at 25 cycles, and probably due to eddy currents in the sheath. The 62.5-cycle test could only be carried up to about 400 amperes on account of limited supply, and for that reason some of the more important 25-cycle values are replotted in Fig. 6 and also in Fig. 5, for comparison.

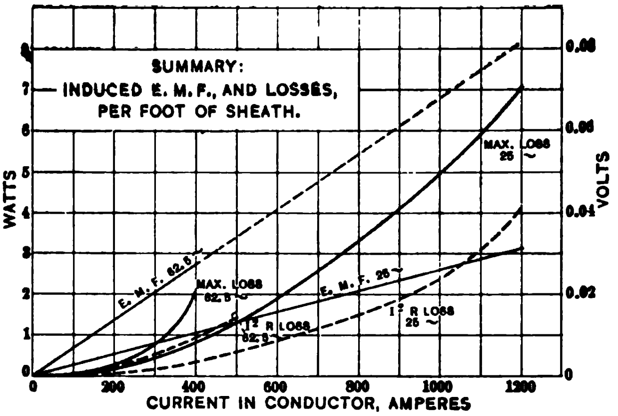

FIG. 7

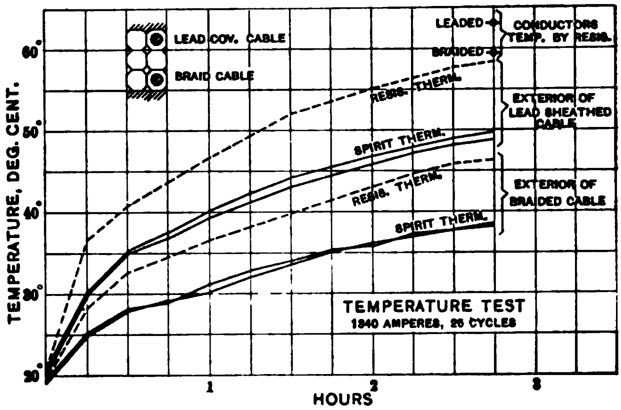

FIG. 8

Fig. 5 is similar to Fig. 3, and is an analysis of the secondary circuit losses at 62.5 cycles. The excess of measured loss over I^2R for the sheath is shown here, as in the 25-cycle test, the ratio being about the same, approximately two to one.

A summary of the foregoing tests is shown in Fig. 7, giving the induced e.m.f. and losses per foot of sheath, for primary currents up to 1200 amperes.

Temperature Tests. A temperature test was made by passing 1340 amperes, 25 cycles, through these two cables in series, and observing the temperature of the outside of the cables until practically constant temperature was reached. The temperature of the conductors was also obtained, by resistance, at the end of the run. Throughout the test, the sheath circuit was closed and a current of 192 amperes flowed in the sheath. The results are given in Fig. 8.

The resistance thermometers were in close contact with the outer surface of the cables, at the breaks in the duct described above. The spirit thermometers were thrust down inside of the ducts, as far as they could be read.

C. T. Mosman (by letter): The discussion has shown the possible need of emphasizing certain points in the paper in order that there may be no misunderstanding of the author's ideas of its range of application.

It is quite evident that the location, arrangement and loading of this duct system are such that to draw conclusions therefrom which will be applicable to the usual city installation would require considerable practical experience with underground systems and unusually good judgment. If it were necessary to carry 81 ducts under a city street and for any considerable distance, undoubtedly an attempt would be made to arrange these ducts in two or three separate sections, sufficiently separated so that there might be an appreciable spacing of earth between the adjacent sections, thus enlarging the exterior radiating surface of the system and consequently its contact with the surrounding soil. This arrangement would be much superior to the idea suggested by Professor Puffer, of having a central air duct or space, which would serve little purpose in carrying off heat unless a definite circulation of air were maintained, and even then it is doubtful if the arrangement would allow of as high carrying capacity per square foot of section as would be obtained by division of the ducts into separate sections.

Apparently Mr. Elden has misunderstood the temperature limitations for the various types of insulation given at the top of the second page of the paper. The temperatures there given are the total temperatures in deg. cent., not temperature rise, and hence are apparently still more at variance with Mr. Elden's ideas. The temperatures given by Mr. Elden are extremely interesting, but it should be noted that they are the temperature rises presumably in deg. cent. of the cable sheath at the manhole above the temperature of the air in the manhole. A reference to Figs. 12 and 15 indicates that there may be considerable difference between these terminal temperatures and the temperatures obtaining at some other point in the duct, Fig. 15 indicating a difference of 28 deg. It should also be borne in mind that some of the cables referred to by Mr. Elden are insulated for high potential, and hence that a very appreciable allowance must be made for the fall of temperature through the insulation, and thus it is safe to assume that if a temperature rise of 30 deg. is obtained at the manhole with the air temperature at 25, or a total temperature on the cable sheath of 55 deg. cent., the temperature of the copper at some point in the duct may be easily in the neighborhood of 100 deg. cent. Cables might operate at such a temperature for a considerable number of years before giving evidence of deterioration. At the same time it does not seem to the speaker that such operation should be considered good practise.

The bonding recommendations made in the paper are suggested as applicable only to the particular installation under consideration, or other very similar installations, and are by no means considered applicable to street service. It should be kept clearly in mind that the cables under consideration in this paper are single-conductor, lead-covered, carrying fairly large currents and hence in no wise comparable with the triple-conductor cable, which would generally be used for carrying three-phase currents in a city system.

In the London *Electrician* of September 2, 1905, appeared an article by Mr. Morris showing that in a triple-conductor cable with insulation between wires of 0.35 in. (8.89 mm.), and a ⅛-in. (3.175-mm.) lead sheath, carrying 50 amperes at 60 cycles, the energy loss in the lead sheath was but 0.3 per cent of the copper loss in the cable, thus indicating that for a triple-conductor cable in a tile or fibre conduit the sheath loss may be neglected. For the same cable in an iron pipe the sheath loss would be increased about 75 per cent. Fig. 23, curve 2, in the author's paper indicates that with the single-conductor cable carrying 450 amperes, a sheath current of 75 amperes might be expected, this test being made at 40 cycles, the sheath current being in this case about 16 per cent of the current in the cable.

In the London *Electrician* of April 15, 1905, is an article by Mr. Field stating that in the case of two cables 12 in. (305 mm.) apart and carrying 200 amperes at 60 cycles, a sheath current of 64.5 amperes was obtained, the sheath current hence being 32 per cent of the current carried by the cable. If proper corrections are made for the difference in frequency and for the difference in the thickness of the lead sheath and the amount of current carried by the cable, I think it will be found that the sheath currents given in the paper are in reasonable agreement.

The limiting capacity of the cables in a duct system should be dependent upon the exterior perimeter of the total conduit section, again indicating the desirability of sectionalizing a large system. The 9 by 9 section under consideration, operating at 2 watts per duct foot (1 ft. = 304.8 mm) or 62 watts per conduit foot, has outside dimensions of approximately 4 by 4.5 ft. (1.2 by 1.37 m.), or a total perimeter of 17 ft. (5.18 m.). If the radiating surface of the top of the system is neglected, there results a perimeter of 13.5 ft. (4.115 m.), hence the radiation must be 12 watts per sq. ft. (0.0929 sq. m.) of radiating surface. From 6 to 12 sq. ft. of radiating surface, neglecting the area of the top, may be considered good practise in the case of manholes containing transformers or other devices giving off considerable heat; the proper limit, of course, depending greatly upon the condition of the surrounding soil, particularly with regard to dampness; hence on this basis the limit of 2.5 watts per duct foot would again appear reasonable.

Professor Puffer has suggested the flooding of the duct system with water in order to increase its capacity. This was one of the first ideas that occurred to us, but it was discarded as not practical. There is no doubt that by this means the capacity of the duct system might be enormously increased, particularly if the water were circulated. The risk of puncture of the cables due to small holes in the lead, the increase of sheath currents, the probability of the lead being subject to chemical action and electrolysis due to impurities contained in the water, and the inconvenience of emptying the system to make it possible to inspect or work upon the cables, and the fact that a portion of the duct system is above the basement floor of a building, are all strong arguments against such an arrangement.

The tests forming the basis of this paper were carried out by Mr. William Clark, who was sent to the plant with very broad instructions to obtain data in the best way available. The work was done in the winter and involved very serious discomfort, and many unexpected difficulties were encountered. The working up of the data required something like 100 curve sheets. Mr. Clark was assisted in the carrying on of the tests by Mr. George A. Burnham and Mr. S. C. Coye.

Mr. Clark has already covered Professor Puffer's inquiry with reference to the testing of the iron wire. It should be borne in mind that no duct contained both an iron wire and a lead cable, and it should also be borne in mind that the principal and most interesting data were obtained by the use of a test coil which could be placed in any desired position in a duct, in this case the iron wire simply serving to produce heat.

Ralph H. Rice (communicated after adjournment): In connection with Mr. Mosman's paper I would like to call attention to the current-carrying capacity allowed by the Board of Supervising Engineers, Chicago Traction. It is shown in the following table:

	Rubber-insulated lead-covered	Paper-insulated lead-covered	Triple braided weatherproof
1 000,000-cir. mil cable amperes	800	1,000	1250
500,000-cir. mil cable amperes	500	600	625
350,000-cir. mil cable amperes	375	425	325
4/0 cable, amperes	—	—	325

It will be seen that this carrying capacity is much more liberal than that indicated on the next to the last page of Mr. Mosman's paper.

We have found no trouble as yet with any of our cables which can be traced to overheating. In explanation of this, two things might be pointed out:

First.—That the duct lines in which these cables are placed are situated in trenches in the ground and not in the basement of a building, as the cables under test.

Second.—Mr. Mosman has tested cables in a conduit section, 9 by 9 ducts. It is the practise of the railway companies in Chicago to restrict the conduit section to a much smaller number of ducts than this. The largest duct section ordinarily used when unprotected by concrete or earth walls is 12 ducts. When we have 16 ducts, or over, the section is broken by a 4-in. (10-cm.) vertical concrete wall, so that in any one compartment there are not more than 12 ducts.

R. W. Atkinson (communicated after adjournment): Mr. Mosman's paper is of very great value in showing limiting carrying capacity in such an unusually large duct system. The writer will confine his discussion largely to two subjects covered by the author. He expects to show that the heat conduction lengthwise along the copper and lead is far less important than seems to have been assumed by the author. We are presenting data from which may be calculated the current which will be induced in the lead sheath of single-conductor cables carrying alternating current. Also data are given showing the amount of voltage induced when the sheaths are insulated from each other so as to prevent the current flowing. The energy loss due to the sheath current is very important in many cases (as for instance that described by the author), but the dangers due to the induced voltages may be even much more serious.

In several places, the author explained some of the results obtained on the assumption "that considerable of the heat generated in the test wires must have been dissipated by the cables operating at low loads." (See pages 761 and 770, this volume.) Also on page 766, he says " the lead sheaths of these cables presumably conducted heat to the end of the ducts and dissipated it to the air in the manholes." The writer has made calculations showing that the influence of the lengthwise heat conduction is negligible as regards either the average temperature or the maximum temperature. We find in handbooks the heat conductivity of copper given as 0.72 g-cal. per deg. cent. per cm. cube. The conductivity of lead is approximately one-eighth as much. For copper, we may put these data in the form 2.01×10^6 thermal ohms (deg. per watt) per mil foot. That is, the heat resistance of 1 ft. (304.8 mm.) of 1,000,000-cir. mil cable is 2.01 thermal ohms, or a heat current of 1 watt will flow lengthwise when there is a difference of temperature between the ends of 2.01 deg. cent. From the dimensions of the cable given, we compute a cross-section area of the lead equal to 760,000 cir. mils. In heat conductivity, this is approximately equivalent to 95,000 cir. mils of copper. Mr. Mosman found the point of maximum temperature as near as 14 ft. (4.3 m.) from one of the manholes. We will make the following very rough assumptions, for an approximate calculation. From Fig. 5, test No. 1, 28 deg. cent. is considerably more than the difference in temperature between any test wire and the lead sheath of the cable at the mouth of the duct in the manhole. For convenience, we will take the resistance of the cable as two ohms per ft. (304.8 mm.) (on the assumption that both lead and copper are available for heat conduction, the resistance is about 10 per cent less than this). Assume that there is no heat conduction along this cable from a greater distance than 14 ft. (4.3 m.). Assume that over the 14 ft. a total of two watts is delivered from the test wire to the unloaded cable. Assume that an equal amount is contributed by each foot of the length, so that 2/14 of a watt is contributed by each foot length. The heat flow, then, in the cable at the duct's mouth will be two watts, and one foot away will be decreased by 2/14 watt, and so on. Two watts heat flow will require a difference of temperature of 4 deg. per foot. The gradient will be gradually reduced until it reaches zero at 14 ft. Accordingly the total temperature difference will be 14 times the average gradient, or 28 deg. cent. Then if our assumptions are true, 2/14 watt of the two watts generated per foot in the test wire could be carried away by a single unloaded cable. This is only 1/14 or about seven per cent of the total heat generated and would be expected to make about that per cent difference in the temperature. Even this amount is very small as compared to the difference expected to be accounted for in this manner. However, our assumptions have very greatly magnified this effect. It will be noted that the difference in temperature between the test wire and the cable is 28 deg. cent. at the duct mouth, and is 2/14 of a degree at the 14 ft. point. We have assumed that there is 2/14 watt flowing from the test wire to the cable at each point. It is very obvious that however good or however poor the intervening duct walls are as heat conductors, many times as much heat will be carried to the cable from the one-ft. portion near the duct's mouth as is carried to it from the one-ft. portion near the 14-ft. mark. More careful calculation along the lines suggested (preferably by the use of calculus) shows that the maximum temperature can be affected by but a small fraction of one per cent. On the assumption that the heat conductivity between the test wire and the cable is very high, about 4.5 watts might be dissipated instead of 2, at each end of the cable. This is slightly over three per cent of the 280 watts dissipated by the test wire, and indicates a *possible maximum* effect upon the average temperature. A calculation similar to the above would have convinced Mr. Mosman that he need fear no errors in his results due to this effect.

The writer has given some attention to the subject of induced current and voltage in armored and lead-covered cables. In a paper by H. W. Fisher* a method of calculation is given, which was developed by the writer. These data are now presented in more concrete form. Referring to Figs. 9 and 10, it will be seen that the voltage induced depends upon the frequency, the distance apart of the cables, and the diameter of the lead sheath. The voltage induced for either 25 or 60 cycles may be read directly from the curves. These data are shown much more readily, as we have done, on logarithmic paper. The current which is induced when the lead circuit is completed is shown for several sizes of lead sheath at both frequencies. Intermediate values may be interpolated fairly closely or may be calculated by the method below.

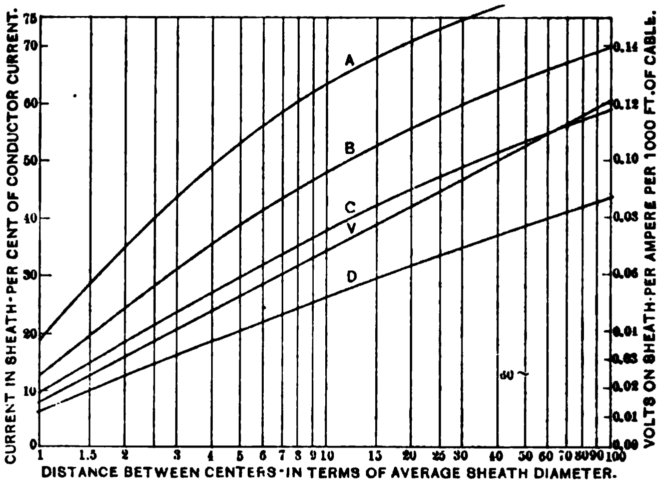

FIG. 9

The curves *V* in Figs. 9 and 10 give either reactance against neutral per 1000 ft. (304.8 m.) of cable, or voltage induced per ampere in the conductor at 60 cycles and at 25 cycles. The formulas for calculating this reactance are

$$X = 0.05295 \log 2 \frac{D}{d}\text{, for 60 cycles}$$

$$X = 0.02207 \log 2 \frac{D}{d}\text{, for 25 cycles}$$

The voltage induced = *IX*, where *I* is the current in the conductor.

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*TRANSACTIONS A. I. E. E., 1909, XXVIII, II, p. 759.

The current induced in the sheath when the circuit is closed equals $\frac{X}{\sqrt{R^2 + X^2}}$, where R is the resistance per 1000 ft. of the lead pipe. (The resistance at 100 deg. fahr. (38 deg. cent.)

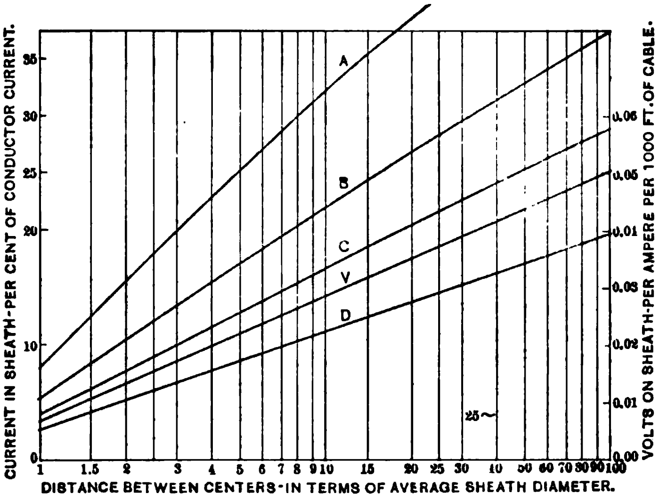


Fig. 10

Figs. 9 and 10

Induced Voltages and Currents in Lead Sheaths

Curve "V" gives the volts to ground on the lead sheath per 1000 ft. per ampere flowing in the conductor. For three-phase circuits the voltage between sheaths equals 1.73 times the value on the curve, or twice this value for single- or two-phase circuits.

Curves *A*, *B*, *C* and *D* represent the current induced in the lead sheaths when they are connected at the ends. 1/8 in. (3.175 mm.) thickness of lead has been assumed. Current is given in per cent of conductor current.

Curve *A* for 3 in. (76.2 mm.) mean diameter of sheath
" *B* " 2 " (50.8 ") " " " "
" *C* " 1.5 " (38.1 ") " " " "
" *D* " 1 " (25.4 ") " " " "

If thickness of sheath is other than 1/8 in., use a diameter for calculation which, with 1/8 in. thickness, will have the same cross-section of lead as has the sheath under consideration. Where the sheath is less than 1 in. in diameter, the current flowing may be taken as approximately proportional to the cross-section of lead.

Power Lost.—If P equals per cent of sheath current in terms of conductor current, add to the conductor resistance $(P/100)^2\ 0.25/d$, d being average sheath diameter. 0.25 is the resistance per 1000 ft. of 1-in. pipe (average diam.), 1/8 in. in thickness. If the thickness is other than 1/8 in., the energy lost is of course inversely proportional to the thickness for a given current.

of a lead pipe having an average diameter of one in. (25.4 mm.) and a thickness of lead of $\frac{1}{8}$ in. (3.175 mm.), is $\frac{1}{4}$ ohm per 1000 ft.) Average diameter refers to the average of the internal and external diameters.

Example.—We take the following data from the paper of the author—Outside diameter of cable 1.65 in.; thickness of lead 0.125 in.; average diameter of lead 1.52 in.; resistance of lead sheath 0.182 ohms per 1000 ft.; distance between centers of cable (probably) 4 to 5 in.; frequency 40 cycles. We have, then, $\frac{D}{d}$ is 2.63 to 3.28. From curve V, Fig. 10 of this discussion, we find that the reactance at 25 cycles is therefore from 0.019 to 0.0212 ohms per 1000 ft.; the reactance at 40 cycles is then about $0.020 \times \frac{40}{25} = 0.032$. The current in the lead sheath is then $\frac{0.032}{\sqrt{0.182^2 + 0.032^2}} I = 0.173\, I$, that is, 17.3 per cent of the current in the conductor. Mr. Mosman gives for the cables in the ducts under these conditions, 16.5 per cent (test No. 2, Fig. 23.).

Mr. Mosman finds, in another test, 33 per cent as much current in the sheath as in the conductor, after making allowance for resistance of bonds. He has made the correction as though for direct current. This is approximately correct, as the reactance is relatively small even in this case. Hence, there will be no error introduced if we assume the reactance voltage to be in proportion to the current produced, that is, that there is approximately 1.9 times the voltage in this case as in the former case. At 25 cycles, this would be 0.020 × 0.19, or 0.038 ohms per 1000 ft. From the same curve, we find that this reactance is obtained when $\frac{D}{d}$ is approximately 26. The separation between the centers of the cable in this test must have been approximately 1.52 in. × 26 = 40 in. (102 cm.). We have worked backwards purposely in this case, as the separation is not given in the report of this test, and cannot be deduced from the probable dimensions of the system as in the other case. We would not expect a close agreement, but one only roughly approximate, between this calculated value and the distance actually obtained in the test, since a very small difference in the value of the induced current found would make a very large change in this calculated value. Conversely, when it is desired to know the current which will flow, it is unnecessary to know accurately the distance between centers, as a considerable change in distance can be made with comparatively slight effect upon current produced.

We have presented the data with two-fold purpose, first, to make available a ready method of pre-determining conditions which will exist. The second reason is because we consider the unqualified recommendation to insulate the sheath of single-conductor alternating-current cables in order to prevent sheath current, an exceedingly dangerous one. Moreover, we believe that the lead sheath should be solidly grounded at some point instead of through a resistance. Otherwise, unless the station is of very limited output, an accidental ground on any of the cables means full station voltage impressed upon the entire sheath of the cable in question. Under the specific conditions mentioned in the paper, this would mean full station voltage upon all cables of one phase. Under these conditions, it is very improbable that the first ground produced would be the only one upon the system. It would be quite possible for arcs at different points to melt holes in the sheath and burn through the insulation to the conductors.

When sheaths are insulated the normal voltage to ground will be something of no mean value; as calculated above, the reactance per 1000 ft. (304.8 m.) is 0.032 ohms. With 500 amperes flowing in the conductor, this means a voltage to ground of 16 per 1000 ft. The voltage between cables of the opposite phase would be about 30 volts. If this were the maximum value encountered, it might not be serious and might cause no damage, if the means of insulation described by Mr. Mosman were in use.

However, we may have excessive sheath voltages induced if a short circuit occurs in the substation at the end of a cable, without any failure whatever on the part of the cable itself. If the voltage is maintained at the power house during a short circuit, during the maintenance of the short circuit, there will be induced in the cable sheath a difference of potential nearly equal to the power house voltage. For example—the reactance at 40 cycles of a circuit consisting of two 1,000,000-cir. mil cables 1000 ft. long, at 4-in. (102-mm.) centers, is 0.067 ohms at 40 cycles. The resistance is 0.02 ohms, and resulting impedance 0.07 ohms. If the station voltage is 1000 volts and is maintained, more than 14,000 amperes will flow in short circuit. The reactance of lead sheath will be, for the 2000 ft. (609.6 m.), approximately 0.06 ohms. This multiplied, by the short circuit current, gives more than 850 volts. The damage which might be occasioned by the presence of such a voltage can still better be imagined when it is noted that the current which can flow if the opportunity is given, is a very considerable percentage of the short-circuit current flowing in the cable, in this case about 2500 amperes. It may be taken as a general rule, that, regardless of other conditions, where the lead sheaths are insulated from each other when a short circuit occurs at the end of the cable, a very considerable percentage of the cable voltage will be induced between the lead sheaths. This is both dangerous to the cables themselves and to the life of anyone approaching the supposedly grounded lead sheath.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

COMPRESSION CHAMBER LIGHTNING ARRESTER AND THE PROTECTION OF DISTRIBUTION CIRCUITS

BY E. E. F. CREIGHTON AND F. R. SHAVOR

The object of this paper is to describe a new form of lightning arrester in which the attainment of low cost was the principal motive of the design, and to note the improvement the application of this arrester will have on the methods and efficiencies of protection of distribution circuits. This is the first step toward the complete solution of the problem of discontinuity of service and injury of transformers due to lightning. This is to be the subject of continuous study until the desirable condition is reached. The end seems already in view, although not all of the material is sufficiently completed to be made a part of this paper.

During the past few years relatively little experimental work has been devoted to the multigap lightning arrester. Even now after much further experimentation no principle stated then is rendered questionable. One new feature in the operation of the arrester has been added. If there is apparently a partial or temporary recession of practise previously laid down it comes entirely from the desire to lower costs, and other changes are made to minimize the effect of the recession.

There has been a demand for years for an inexpensive arrester for the protection of small installations where the revenue from, and cost of the installation would not justify the expenditure for the best arrester.

Furthermore, the best practise in protecting 2300-volt pole transformers *absolutely demands* that the arrester be placed on the same pole with the transformer. To fulfill this condition an inexpensive arrester is necessary. The practise of placing three or four arresters per mile, regardless of the location of the transformers, is ineffective. Experience shows that lightning potentials are very much concentrated, and an arrester placed even at the distance of an adjacent pole from a transformer may be rendered unprotective. This is a condition which can be produced in the laboratory experiments.

CONSTRUCTION OF THE COMPRESSION CHAMBER ARRESTER

The compression chamber arrester is a particular design of the well-known multigap arrester. The cost of this arrester has been reduced principally by making it self-housed. The other standard design of multigap arrester was made for indoor work, and when used outdoors requires a wooden box for housing it. This wooden box is comparable in expense to the arrester itself.

Fig. 1 shows the arrangement of the parts of the compression chamber arrester. Fig. 2 shows the assembled arrester and Fig. 3 the disassembled parts. On the outside, Fig. 1, there is a porcelain base with four screw holes to connect it to a cross-arm. Immediately inside of this base are the *antennae*. The antennae vary in form in different arresters, but in this case they consist of two metal strips in the form of a U that fit inside of the holder or base. Inside of these antennæ is placed a straight porcelain tube. The porcelain tube is held in place by insulating cement. Inside the porcelain tube the gap units are placed. Each gap unit consists of two punched metal hats of special alloy. The crowns of these hats are turned so they face each other, and both crowns are knurled. Between the rims of the two metal hats there is a short porcelain tube which holds the crowns of the

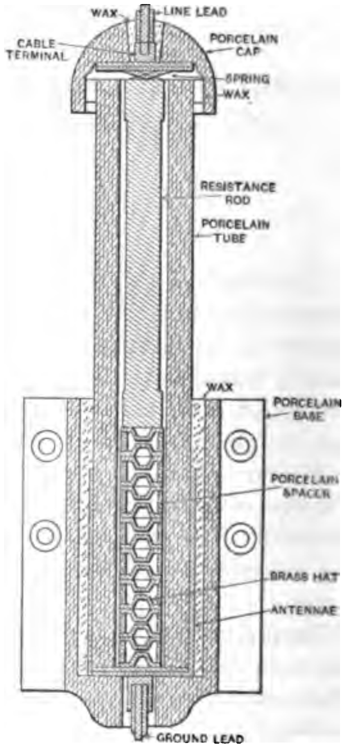


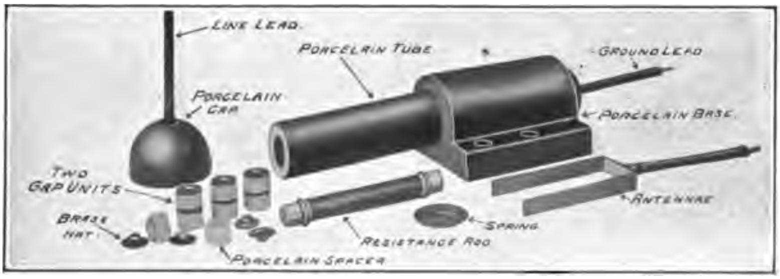
FIG. 1—DETAILED CROSS-SECTION OF ARRESTER.

[CREIGHTON AND SHAVOR]

FIG. 2—EXTERIOR VIEW OF ARRESTER.

[CREIGHTON AND SHAVOR]

FIG. 6—EXTERIOR VIEW OF HIGH-POTENTIAL ARRESTER—10,000 VOLTS.



[CREIGHTON AND SHAVOR]

FIG. 3—DISASSEMBLED VIEW OF ARRESTER.

metal hats about 1/32 in. (0.8 mm.) apart. These gap units are stacked one on top of the other inside the porcelain tube between the arms of the antennæ. On top of the gap units is placed a resistance rod of low ohmic value. The gap units and resistance rods fill the long porcelain tube. On top of the resistance rod a spring contact is made, and a porcelain cap is fitted over the end of the tube and cemented there. Through the porcelain cap the connecting wire projects. The ground connection is a wire which passes through the bottom of the base and is connected to the antennæ as well as the lower gap unit. The arrester is hermetically sealed so that no dust, dirt, or moisture can get inside.

Characteristics of the Arrester

The arrester required thousands of actual tests to determine its characteristics and choose the proper values of the factors involved. Some idea of this work and the methods is given at the end of this paper in a condensed form. At the present time it is desired only to review its distinctive characteristics, such as the series resistance, gap units, spark potential, short-circuit conditions, endurance under rapid strokes, life of the arrester, tests of arresters for protecting transformers, etc.

Series Resistance. Some years ago a complete development was made of a multigap arrester in which the series resistance was shunted by gaps. This feature has proved of very great value for heavy discharges of lightning. There is no possible doubt that when a heavy discharge of lightning is thrown on the arrester, the ohmic drop of potential in a series resistance is objectionable. Therefore, it is necessary to justify the abandonment of this valuable principle in one form of this new arrester.

Compression chamber arresters are not designed for the protection of valuable station apparatus where the maximum possible protective value is essential to the continuity of service. But the arrester is designed especially to protect small transformers where the cost is comparatively slight. The arrester, therefore, must have a cost that is compatible with the cost of the small transformer. At the same time the arrester must maintain a very high degree of protection. Due to the high factor of safety in the insulation in the design of distribution transformers, this is made possible in the cheap arrester. Due to the effect of the antennæ in this arrester, which will be described later, it is possible to use more than the usual number of gaps in series. In consequence, the resistance in series with the gaps may be kept at a very low value. The average value of this resistance is 23 ohms. The discharge current to ground per phase will be equal to the lightning potential divided by 23 ohms.

The next question is, what is the limit of the safe value of lightning potential which can be applied to the transformer? The high factor of safety, *i.e.*, five, given to the insulation of these transformers, as compared to the usual factor of 2.5, is the element which gives justification, as will be shown, to the use of series resistance. All these transformers are tested for one minute to a potential of 10,000 volts. Therefore, momentarily, they will stand a very much higher potential. This higher value for the momentary application is unknown, but 15,000 volts is surely a safe value to assume. With a lightning stroke of 15,000 volts at the terminal of the arrester, the discharge rate of the arrester will be 15,000 divided by 23, which is approximately 650 amperes. In other words, this arrester applied to this particular transformer has a discharge rate of 650 amperes before the lightning potential reaches a dangerous zone. From both theory and practise, this value seems to be sufficient. In the aluminum arrester the design is made such as to give this discharge rate of current at double potential.

The Antennæ. Turning next to the subject of spark potential, we have known for years that an antenna placed near a multigap arrester always reduces this spark potential. In fact, any ground surface in the neighborhood of the arrester will produce this effect. It was one of the difficulties we had to contend with in the design. An arrester designed to be placed very near a connecting wall would sometimes have such a low spark potential as to require more gaps placed in series. On account of the particular conditions of the design of the standard multigap arrester, it was not found feasible to utilize the antennæ. However, with the form of insulation in the compression chamber arrester the antennæ can be easily applied.

In theory the antennæ make the arrester more sensitive by increasing the electrostatic capacity of each electrode to ground, while the electrostatic capacity to the adjacent electrodes remains constant. This theory was given by Dr. Steinmetz in 1906.

The use of the antennæ gives, first of all, uniformity in the spark potential regardless of the surroundings. In the next place, the use of the antennæ reduces the spark potential of the series of gaps used in this arrester, to exactly one-half of the potential without the antennæ. This permits the use of twice as many gaps as would otherwise be possible. Each gap has the function of extinguishing the arc of a certain potential applied to it. Therefore, when the number of gaps is doubled, the arc-extinguishing power of the arrester is greatly magnified.

Characteristics of the Gap Unit. Each gap is enclosed in a sealed chamber, and any expansion of gases in that chamber will cause an increase in pressure, which, as is well known, tends to extinguish an arc. Furthermore, the porcelain tube which encloses the gap has its cooling surface in close proximity to the arc. The cooling effect of this porcelain surface is demonstrated by the grayish deposit which takes place after the arrester has discharged many thousands of times.

The spark potential of this arrester can be set at any desired value. The most desirable value seems to be about 0.7 of the value of the potential at which the transformer insulation is tested. This spark potential is apparently safe for the transformer, and at the same time it is sufficiently far above the potential of the recurring type of internal surges as to make the arrester safe from destruction by these surges. In other words, the arrester is designed for lightning and only such internal surges as reach a dangerously high value. For the general protection against internal surges on a 2300-volt system it is better to trust to one aluminum arrester situated in a station. The aluminum arrester can have a spark potential as low as one-fourth and even one-fifth the tested potential of the transformers and still be safely operated on 2300 volts. It will be seen that by following this practise the compression chamber arrester will be called on to carry successive discharges very rarely. As to successive lightning discharges, the compression chamber arrester is designed sufficiently strong to withstand many more successive discharges than ever take place. This is explained later.

Short-Circuit Conditions. It is therefore necessary to take precautions only to arrange to clear the line of the arrester in case some extraordinary condition shall arise, such as a direct stroke or a cross with some high-tension circuit, or any unforeseen condition which produces a continuous discharge in the arrester. This is accomplished by the breaking of the porcelain tube from the heat given out by the resistance rod. Each resistance rod has a certain capacity for absorbing heat. Since the amount of energy concentrated in a resistance rod is very great as compared with its radiating surface, the rod will heat so rapidly that one hardly needs to consider the radiation as a factor in a lightning arrester rod. If the discharges are practically continuous the rod will quickly heat to incandescence, and will crack off the tube. The cap will then dangle from the wire but the line will be free of short circuits. Inspection, then, of the lightning arrester will consist simply in visual observation from the bottom of the pole. Since the resistance rod is the weakest spot in the arrester, one may conclude that if the arrester is not broken, it is in good condition. Still further proof of this will be given later.

Endurance of the Arrester to Withstand Rapid Strokes. In order to determine the strength of the arrester to withstand rapid successive discharges, an arrester had applied at its terminals, 170 per cent of its dynamic potential. The discharges were made through the gaps by means of an induction coil. This induction coil was operated from a make-and-break contact which made thirty strokes per second. An oscillograph was placed in series with the arrester in order to measure the number of strokes applied to it. Forty-five strokes were applied during 1.5 seconds without causing any damage to the arrester. The greatest known number of successive strokes from lightning in a second is shown by some photographs. This number is only a fraction of the number applied to the arrester. Tests made in connection with Mr. J. A. Clay on the Animas Water Power Company's line, 1907, showed that nearly every stroke of lightning consisted of a succession of discharges, and that the usual number lay in the range of 3 to 9. Sometimes these are distributed over an entire second, but usually they occupied only a very small fraction of a second. As already stated, the limit of the number of discharges is set by the heating of the resistance rod. If the successive discharges are spread out with several seconds between, then the radiation from the resistance rod is sufficient to give the arrester a very long life for such discharges. The actual limit for one of these rods is 50,000 joules, which corresponds to the normal dynamic discharge current for ¼ sec. on one type of resistance rod.

Life of the Arrester. In order to determine whether it would be desirable to leave the arrester open at the top so that the gap units could be replaced after they had worn out, a number of life runs were made on the 2300-volt compression chamber arrester to determine how frequently such a change would need to be made. The result showed that the life of the arrester was so great that it was entirely unnecessary to make any provisions for changing the gaps. For example, discharges were applied to the arrester with intervals of one minute between. These discharges were continued up to 9000. The arrester was tested with the oscillograph at about every 2000 discharges to determine its condition, and the spark potential was taken. Both these tests showed that the arrester was at all times of the run in as good a condition as at the beginning. The rectifying power of the gaps was the same, and the spark potential of the arrester, even after the 9000 discharges, remained constant. In other words, these discharges did not burn away sufficient metal from the surface of the electrodes to increase the spark potential, although a dynamic potential of 70 per cent above normal was applied to the arrester. The insulation between electrodes, measured by a "megger," was far above 2000 megohms—practically infinite. When a gap unit was split open a considerable deposit of soft grayish material was found on the walls of the chamber and around the gap, but this material was non-conducting.

TESTS OF ARRESTERS PROTECTING TRANSFORMERS

These tests were made in the laboratory with artificial lightning. An explanation is due at the outset that one cannot reproduce in the laboratory all the forms of lightning that occur from the elements, yet certain forms of laboratory tests along this line of endeavor are not to be despised. In this case we produced an artificial lightning stroke at the terminals of the transformer, of sufficient strength to puncture the insulation between primary and secondary. All we can say of this lightning stroke is that it was of unusual strength as compared to the ones which ordinarily occur on a 2300-volt line. A large number of transformers, both new and old, were available for testing the protective value of the lightning arrester.

The following set of tests is illustrative of the statements regarding the protective value of the arrester. A 2300-volt transformer was placed in parallel with a lightning arrester and subjected to the discharges of artificial lightning. Three thousand discharges were made and no damage occurred to the transformer. The arrester was then removed and the transformer punctured between primary and secondary on the very first discharge. The question next arose whether the transformer had not been damaged by the 3000 discharges, so another transformer was placed in circuit without the lightning arrester.

The first discharge of artificial lightning punctured the transformer between primary and secondary. Again, another transformer with the same insulation was placed in parallel with a lightning arrester and subjected to successive discharges. After 3500 discharges had passed, it was decided that no damage could be done to the transformer while protected by the arrester and the arrester was removed. Again, as before, on the very first discharge without protection, the transformer failed.

These tests tell us that the lightning arrester will give protection against strokes that will damage the transformer. They do not tell us that the arrester will give protection against all strokes, since it is conceivable that a lightning stroke may have a rate of discharge such that an ohmic drop across the resistance rod might be sufficient to give a dangerous potential across the terminals of the transformer. On the other hand, to offset this possibility, there is always a limited spark potential around the bushing on the transformer and it is only necessary to make this spark potential somewhat lower than the spark potential between primary and secondary in order to minimize the dangers of even a direct stroke.

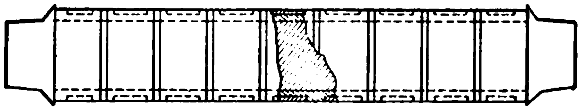


FIG. 4—RESISTANCE ROD, ASSEMBLED WITH BRASS RINGS.

PROTECTION AGAINST OHMIC DROP ALONG RESISTANCE RODS OF THE ARRESTER. BY-PASSING THE ROD

It is conceded that for this 2300-volt arrester the ohmic resistance in series with the arrester introduces an undesirable element when the current in the lightning stroke exceeds 650 amperes. Dr. Steinmetz has shown that the discharge of a surge traveling along a line cannot exceed a certain value of current per volt due to the inherent inductance of the transmission line. These calculations give a considerable confidence that the currents in the lightning arrester circuit scarcely ever approach 600 amperes. Long experience with the aluminum arrester with its 600 amperes discharge rate at double potential also shows that the lightning discharge which exceeds this value is exceedingly rare. These elements, taken together with the desire to keep the price of the arrester within a value compatible with the price of a small transformer and the value of uninterrupted service, makes us adopt the design in the form shown in this paper.

In order to meet the conditions of installation between the small pole transformer and the important apparatus in the power house, an intermediate solution of the problem is made by a compromise between the standard graded shunt resistance type and the arrester just described. The resistance rod is by-passed by a set of multigaps consisting of brass rings placed around the rod. There is a small gap between adjacent rings. See Fig. 4.

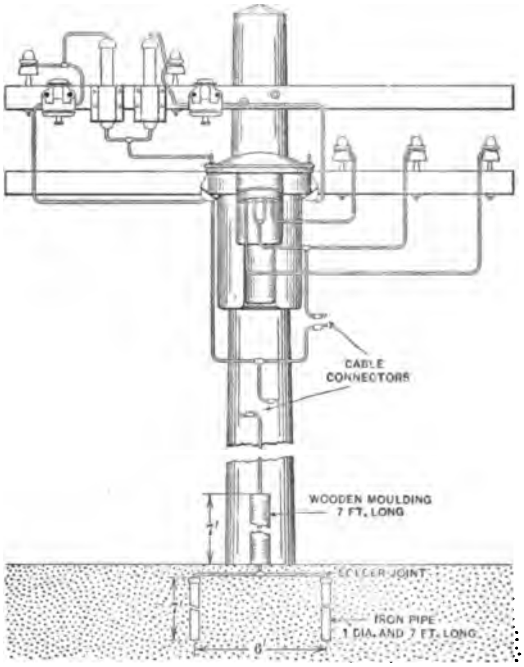


FIG. 5—APPARATUS AND CONNECTIONS FOR LIGHTNING PROTECTION OF INDIVIDUAL TRANSFORMERS.

RECOMMENDATIONS FOR THE INSTALLATION OF ARRESTERS FOR PROTECTING DISTRIBUTION TRANSFORMERS

It seems desirable to include in this paper recommendations for the installation of the arresters. There are some features which are of primary importance, and others which have to be varied somewhat according to the local conditions. Fig. 5 shows the installation of lightning arresters and 2300-volt transformer on a pole for a non-grounded neutral circuit. The relative location of arresters and transformers may be varied to suit the local conditions. Where a grounded neutral circuit is used, only one of these arresters is necessary, the arrester being connected directly across the transformer, and a small extra gap added between the neutral wire and the wire which runs down the pole to earth. The assumption is made in this case that the neutral wire is grounded only at the substation. Again, some difference will be found in the installation according to whether the practise of grounding the secondary is followed or not. The figure shows the connection where the secondary is grounded. If the conditions are the contrary, it is not intended to recommend the grounding of the secondary at the transformer in the manner shown. In fact, the secondary could in any case be grounded through a single unit gap. This gap is made up in the same way as the arrester already described, but it is not illustrated in this paper. Recommendations are reduced to a very brief form in the following list:

1. Install lightning arresters on the same pole on which the transformer is placed.

2. Install an arrester at every transformer.

3. Make the connections from a line wire through the arrester to the transformer case, as short and direct as possible.

4. In making the connections between the lightning arrester and the line, have the point of contact not vertically above the wooden crossarm or any connecting parts in the neighborhood. The idea in this precaution is to prevent trouble in the extreme case of damage to the arrester. For with a continuous discharge in the arrester, the resistance rod will finally heat and crack the porcelain. The cap will break loose and will dangle free of any possible persistent short circuit.

5. Connect the arresters, in general, on the line side of the transformer fuses.

6. Ground the transformer case by means of an iron or copper wire. Since the lightning arrester is grounded onto the case, the drop of potential down the pole along the ground wire is of less consequence than in the former practise when the case was not grounded. Therefore, cheap telegraph wire can be used for the connection between the transformer case and the pipe-earth.

7. If bare wire is used, it is recommended that in some cases a wooden strip be placed over the ground wire for a distance of about 7 ft. (2.1 m.) from the ground up. This addition is used to avoid danger of shock from the ground wire when a cross occurs between a primary and the ground. A cross continued

long enough sometimes dries out the earth connection. There are many cases and places where this is not necessary. Insulated wire may be substituted for the wooden strip.

8. At some point part way up the pole place a clasp connector. This connector is to be opened by the lineman and the ends bent back, when he climbs the pole, in order to insulate the transformer from ground by means of the intervening wood of the pole.

9. If the practise is already followed of grounding the secondary, then use either a small gap between the secondary and ground wire of the arrester or ground the case of the transformer directly on to the secondary through a connector. This connector is also to be opened by the lineman as a matter of safety when he is working around the transformer.

10. For the earth connection in the usual soil, drive a one-in. (2.5 cm.) pipe in to a depth of six to nine ft. (1.8 to 2.7 m.) A shallow hole should be scooped out at the surface of the ground and the top of the pipe driven below the surface. In unusual conditions of very dry, sandy, or gravelly soil, two ground pipes, six ft. (1.8 m.) apart, may be desirable. If the ground wire is protected from corrosion it can be carried directly to each of the pipes. A soldered joint on the pipe is desirable.

11. The earth should be scooped out several inches below the soldered joint and several double handfuls of salt placed in this basin. It is desirable to add some water at the same time. The earth can then be filled in to the level.

Due to varying conditions and tastes, the method of making the earth connection and the materials to be used can be left somewhat to the discretion of the one making the installation.

The object is to have a pipe penetrate into the earth at some convenient distance greater than six ft. (1.8 m.), to have a connection between the grounding wire and the pipe earth which will not be corroded or pulled off, leaving a large gap, and to keep the salt solution away from the soldered joint as much as possible so as to prevent local corrosion at the joint.

As a suggestion, it might be well to use No. 10 or No. 12 insulated wire from each pipe earth to the lower joint of the connector which is placed as a break in the vertical wire, and use iron wire from there up, the iron wire being stapled to the pole.

It is *very important* to note in connection with this practise, which may seem less rigid in regard to grounding than has previously been recommended, that the conditions are different, due to the connection of the lightning arrester to the transformer case.

The drop of potential down the connecting wire on the pole and through the resistance of the earth connection is thereby rendered of comparatively little importance.

In regard to the cost of the materials for this method of grounding, the galvanized iron telegraph wire, from the top of the pole to the pipe earth, will cost about 6 cents. The cost of plain iron pipe one in. (2.5 cm.) in diameter is about 4 cents per ft. Therefore, a pipe 8 ft. (2.4 m.) long would have a cost of 32 cents. The galvanized iron pipes cost one cent more per foot.

It is difficult to see the need of using galvanized iron pipe because the plain iron pipe will last for ten years at least.

By following the practise recommended above, the cost of installation of the lightning arrester, including the cost of the ground wire earth pipes, is all reduced to a small fraction of the cost that was formerly found necessary.

SOME DETAILS IN THE DEVELOPMENT OF THE LIGHTNING ARRESTER

Compression Chamber Arrester for Higher Potentials. There is less demand for an arrester for potentials above 4000 volts grounded neutral. The same design is applicable, however, to the higher potentials. In certain isolated cases this arrester is applicable. Fig. 6, Plate XXXVI, shows the form of a compression chamber arrester for 10,000-volt circuits.

Some Miscellaneous Notes and Tests. In former years it was thought that the design of a lightning arrester required a considerable degree of imagination. Little twists, points, capacities, and fantastic contrivances were placed in the path of the lightning to confine it, and while it was all mixed up in its directions it was to be slid off harmlessly to the ground. In reality the design of a lightning arrester is a relatively prosaic affair. Nothing is left to chance. A test can be devised to gain some knowledge of every factor.

To give full details of the experimental determination of the factors involved in an arrester would, we fear, be of little interest to the members of the Institute. A brief statement of each step may be of interest to indicate the methods and care that are involved. This brief account follows:

Tests were made to determine—

1. If gaps enclosed by hollow cylindrical spacers, which determine a certain gap length between electrodes, will extinguish the dynamic arc without destroying the enclosing spacer.

Tests were made using hollow cylindrical spacers of different lengths and different inside diameters. Tests proved the arrangement to be practical and efficient.

2. The minimum gap length permissible to prevent bridging of the gaps by molten metal thrown from the arc crater during discharge, under conditions noted in (1). (Standard lightning arrester electrode metal used in test.)

3. The possibility of using punched sheet metal electrodes versus solid metal electrodes of like material for efficiency and durability.

4. If discharge faces on the electrodes should be smooth or knurled.

5. The material to be used for spacers.

Many materials were tried, among which were fiber (treated and untreated), hard rubber, glass and porcelain.

6. Form and size of discharge face of the electrodes.

7. Inside diameter of porcelain spacer to insure no assistance to dynamic arc in holding across the gap.

8. Length of porcelain spacer to obviate any possibility of deposit from material thrown off by the arc forming a conducting surface from one electrode to the other, thereby short-circuiting the gap.

The length was determined at 17/32 in. (5.5 mm.). 9000 consecutive discharges on a 2300-volt circuit, using sealed gap units, failed to render the surface of the spacer conductive.

9. Leakage factor of porcelain spacer 17/32 in. (5.5 mm.) long.

The leakage factor for this spacer as found by test on a 60-cycle circuit is 6350 volts, effective.

10. The value of resistance to be used in series with the gaps on a 2300-volt circuit.

A number of tests were made by varying the number of gaps from two to six, also varying the resistance from ten to one hundred ohms

A test was run using a minimum number of gaps (2) and a minimum amount of resistance (10 ohms).

A typical test is shown by the use of three gaps with a 23 ohm resistance rod in series, all of which were enclosed in a porcelain tube. The arrester was sparked over by the use of a static machine.

At the end of 100 discharges taken at intervals of five seconds the temperature rise of the tube above the air was 23 degrees cent. No damage was done to the arrester and no fuses were blown.

11. The effect of water in the containing tube on the operation of the arrester.

The tube was supported in a vertical position with the line end (top) open and only a small hole in the opposite, or ground end. The arrester was then connected across the 2300-volt circuit, using one strand of five-mil boker wire for a series fuse. The test was started using one drop of water every ten seconds and run for 70 minutes.

Most of the water was evaporated.

Boker wire changed for a 20 ampere fuse. Flow of water increased to one drop every 7 seconds, the arrester being subjected to a static discharge every two minutes. Tests run 45 minutes; operation of the arrester was normal.

Flow of water increased to 85 drops per minute and run for 15 minutes. No trouble developed.

Flow of water increased to a tiny stream. Some steam given off. No fuses blown. Temperature of the tube 28 degrees cent above the air.

Flow of water increased to one pint per minute. No trouble developed. Temperature of tube decreased to 15 degrees cent. above the air. No fuses blown.

Several porcelain spacers were soaked in water for two days. The effect on spark potential of the gap, using these spacers, was not material.

12. The rectifying power of various metals and alloys in form of sheet metal electrodes, as now used in the arresters, and also in form of our standard lightning arrester cylinders.

The amount of zinc volatilized during the life of the sheet metal electrodes is minute. Measurements were taken before and after 500 discharges, at 100-ampere discharge rate, applied to the gaps. The result was a gain of two milligrams in one electrode and a loss of 3 milligrams in a total of three others. This amount was too small to be accurately measured with the available balances.

13. Many tests were made which can be mentioned only in a general way. Among them were:

Tests to determine the length, size and form of the antennæ.

Tests to determine the equivalent needle-gap under various conditions, by use of the static machine; Tesla coil; induction coil; 60 cycles; quick break; direct impulse and lightning generator.

Tests to determine per cent surge; per cent spark potential; etc

Many oscillograms have been taken at critical points in different tests and on endurance runs.

14. Curves were run to show the following:

a. Minimum length of antenna to be used. Minimum length of antenna to give the maximum capacity effect was determined at 87.5 per cent of the total length of number of gaps used.

b. Spark-over potential of containing tube. Tube both wet and dry. Test made only to limits of 10,000-volt arrester (50 gaps). Antenna at 87.5 per cent of length of gaps safe. Spark over potential to support when dry 100,000 volts. Spark-over potential to support when wet 80,000 volts. Factor of safety is 8.

c. Spark potential of gaps for high voltage arresters; gaps varied: antenna 87.5 per cent total length of gaps. Fifty gaps spark over at 21,000 volts at 60 cycles.

d. Antenna surrounding containing tube versus 1/2 in. (1.2 cm.) strips on opposite sides. Antenna surrounding tube requires less spark potential than ½ in. (1.2 cm.) strips. (6.4 per cent. less for 4 gaps to 6.8 per cent less for 50 gaps.)

e. Spark potential using antennæ versus no antennæ. Removing the antennæ raises the spark potential 100 per cent.

f. Spark potential, with antennæ, using single tube versus two tubes in series. Using two tubes in series raises the spark potential about 20 per cent. Therefore, all the gaps for one leg of an arrester should be assembled in one tube if at all possible to so do.

g. Spark potential tests: Antennæ connected to grounded end versus antennæ connected to line end of arrester. The antennæ connected to the line end of the arrester raise the spark potential of the arrester about 10 per cent for low voltages and from 15 to 20 per cent for higher voltages (10,000-volt arrester).

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

HUMAN ACCURACY: MULTI-RECORDER FOR LIGHTNING PHENOMENA AND SWITCHING

BY E. E. F. CREIGHTON, H. E. NICHOLS AND P. E. HOSEGOOD

The object of this paper is to describe a new instrument which will record the time, to the second, of a phenomenon of any kind that can be made to close an electrical contact. Besides recording whether a phenomenon is starting or stopping, a printed record is made of the day of the week, a.m. or p.m., the hour, minute, and second. The highest number of records put on a sheet by a single one of these instruments so far is thirty. The instrument is capable of recording a movement of all of its pencils or type wheels simultaneously, or the movement of any lesser number. Every record shows the position of every type wheel whether it moves or not. The instrument records only to the nearest second, but in case of successive discharges during a single second their relative precedence is noted by giving them successive prints of the same second. In this manner the recorder will split a second into about four parts. The manner of operation will be described later.

The field for this device in theoretical and practical investigations on transient electrical phenomena is immediately evident to those interested in this subject. The field in practical applications of electricity is not so evident. It is thought, however, that this instrument falls in that class of devices for which there is no apparent demand before they appear but which become somewhat of a necessity afterwards.

As electrical distribution in lighting, motive power, and railways becomes more standardized and conventionalized there. is an increasing demand for higher reliability from employees and an imperative need of knowing what the apparatus is doing, especially during periods when accidents are taking place. So long as a plant or railway runs along smoothly, knowledge of simple routine duties is sufficient. During times of trouble there is an immediate demand for the highest knowledge and quick, accurate judgment. The man with such knowledge and judgment has demands on his time which put him out of reach when he is most needed at the scene of trouble. Grant that he has chosen his helpers well—that they are honest, loyal, and conscientious—still there is no guarantee that they will be able to meet the situation. There enters a psychological factor. What will a man do under stress and excitement? His conscientiousness may be the factor that inhibits quick and accurate action. After an accident to a power plant, how is an engineer to know whether the trouble was due to faulty manipulation of the switches or some unavoidable failures of the insulation? Too often a localized trouble is made into a general interruption by a mistaken operation of a switch. How can the reliable operators be picked out? Surely not by their good characteristics under normal conditions of emotion.

Several personal experiences will be given to illustrate the fallibility of observation, especially during periods of mental or nervous stress, and the effects that the characteristics of the individual have in noting their observations.

An example of disagreement in noting simple phenomena occurred in Colorado, 1907. Mr. F. W. Peek, Jr., and one of the writers were making studies of lightning effects in conjunction with Mr. John Clay, superintendent of the Animas Power and Water Company. A heavy lightning stroke started noisy arcs between some terminals and the ceiling, six feet above. There were two of these arcs, making twelve feet total length and absorbing the entire power of the plant. When the trouble started Mr. Clay was outside the building, Mr. Peek was in the third floor of the high-tension gallery, and one of the writers was on the main, ground floor. When the arc was finally put out by the hand manipulation of a faulty oil switch located on the third floor of the high-tension gallery Mr. Clay and the writer were in the gallery, and Mr. Peek was on the floor. Later, we compared notes of the sequence of events, such as the lightning stroke, the starting of the arc, the precipitate exit from the station of several linemen, the entrance of Mr. Clay, the discharge of lightning arresters, the opening of secondary switches and our own movements, up to the time the faulty high-tension switch was opened by hand manipulation. They made three distinct stories, each man positive of his impressions. There was no way of getting at the real truth. We feel we are trained observers, so surely men in power houses with less training could scarcely be censured for wrong impressions. It was extremely important to all of us that the arc should be extinguished immediately so as not to damage the building. The nervous tension was, therefore, unusually strong, although it could scarcely be said we were excited.

This illustration calls to mind one recently used by a most eminent practical psychologist in a lecture on the psychology of *evidence*. A professor of law was giving a lecture to third-year students in law, when in the midst of the lecture two students got to quarrelling. Their voices rose in altercation and they finally came to blows. It was necessary finally to eject them from the class room. The situation was so important that the professor had each student write down immediately what he had seen and heard. These sheets of written evidence were collected and tabulations were made of their accuracy. The quarrel had been prearranged, and thoroughly rehearsed beforehand, so that the professor in charge had a record of every word spoken and of every act. In this case the absolute truth was known. This brought a remarkable condition to light. A majority of these men who were being trained for the law, were unable to give accurate evidence of what they had seen and heard. This inaccuracy is exhibited not merely in the matters of which the observer did not feel quite sure, but just as often in the details of which he felt quite sure.

In some studies that were being made of multigap lightning arresters about six years ago one of the engineers from the lightning arrester laboratory was stationed for purposes of study in a power house where two high-tension lines entered from one side. Along this wall were twelve compartments for the different phases of lightning arresters. This occupied the entire length of the room. A person stationed on the opposite side of the room could have all twelve compartments within the range of vision. During storms four compartments at each end of the room had arresters in them which were active. We received reports directly from the laboratory engineer which were noteworthy for their lack of detail. Through the manager of the plant we received details of the discharges on the arrester as taken by one of his best operators. In spite of pressure brought to bear on the laboratory engineer, he could be positive of discharges only over the arrester at which he had been looking, whereas the station operator would describe minutely that discharges had passed over three or four of the different legs of the lightning arrester, widely separated, and would designate which phases, and which lightning arresters. Later we had occasion to look into the matter and we thought at first there was a possibility that this young man had unusual keenness of vision, and we feel quite sure he thought he saw what he wrote down. There was no attempt at deception. It was simply a matter of an imaginative mind. He had naturally an observing disposition and after he had made a short trip through the hills with his gun he would always have interesting stories of incidents of the trip. On one of his trips one of us attended. We found from his descriptions to others afterwards that the incidents were correct but the matter was highly colored by his naturally expansive imagination in associating a simple incident with details which did not actually occur. So far as investigations on lightning were concerned his evidence was worse than none at all, due to his peculiar characteristics of mind. His statements of lightning strokes and effects he had witnessed made interesting fiction, but these statements could not be used as a basis of an engineering development.

In another case an operator, likewise, gave an exceedingly readable account of everything which took place in the station, with records of the exact minutes of each incident, even during times of stress and interruption. These records gave to the reader the impression of great accuracy. I found on questioning, however, that during these times of trouble he was occupied with telephoning, watching the lightning arresters and several various incidental things, and that the records were written up some time subsequently. He thought he remembered the time intervals and could put them down accurately. In this case it was purely a matter of lack of training.

The importance of the psychological aspect of the efficiency of men under trying conditions is appreciated by operating men, as evidenced by the fact that Professor Münsterberg has been asked to develop methods of examination for car motormen which will determine their reliability of action and weakness of judgment in avoiding accidents in their work. In a conference of railway men lasting two days it developed that some of the most reliable men under ordinary conditions, with many years of experience and with trained judgment, have more accidents per year than even some of the raw recruits. There seems to be something that inhibits normal operation of the mind when suddenly called on to decide whether to apply the brakes, apply the reversal, or increase the speed.

A valuable recording device was described at the annual meeting of the Institute last year. This device recorded the exact position of the synchroscope when generators were paralleled. It was reported that at first the men were very disgruntled at having an automatic apparatus used to check up their best endeavors. Later, however, this feeling passed away.

If one is really to run a business, nothing should be left to chance or haphazard judgment. This statement involves the fundamental law of success in running any business or in filling any position of responsibility. Know what is going on. It is a duty. In any standardized line of activity, if something goes wrong there is no excuse for the engineer. His profession is to know and to foresee. He is the guardian of the greatest proportion of the affairs of material things in the world. Since he has made a success of these affairs he is constantly being called on to extend his methods of exactitude to human affairs. Although there is no excuse, there may be an explanation for a calamity. There is no balm, however, to the unfortunate investor and stockholder in an explanation. It may be desirable to run a certain degree of risk in the possible loss of apparatus and income, but this risk must be run with the full understanding that it is more than counterbalanced by the interest on the investment that would otherwise be needed. Incidentally, a sinking fund should be provided to cover this risk the same as to cover interest on an investment.

The means of obtaining knowledge by the engineer is in no way of the nature of espionage. The case of the synchroscope, previously cited, is a good illustration. To avoid an interruption of supply of electricity to hundreds of thousands of users in Chicago, to say nothing of the cost of damage to apparatus, it is necessary to have a spare machine not only at the same frequency and potential as the other machines before closing the generator switch which connects it to the system, but it must also be in the same phase relation. On the part of the switchboard attendant there must be not only certainty of the position of the needle of the synchroscope but there must be knowledge of the time of mechanical motion of the switch and the lead or lag due to the personal equation. The wisest man in the world must have some device or method in order to determine his personal equation. Even the wisest man may have an unreliable personal equation for use in synchronizing alternators. It is the engineer's affair to know this, to utilize the mental wisdom in its place, and also to train the man with manipulating ability. The engineers who devised the recording synchroscope state that it not only gave to the one responsible for the proper operation of the plant a reliable record, but it gave also to the attendant a means of finding himself and of improving his work, which was previously impossible.

A switchboard room is the brain of the electric system. Improper switching is a curable electric insanity. Great losses have been caused by mistakes in switching and there has been no evidence left to indicate the mistake and no possibility of justly placing the blame. In such cases a disconcerting feature is the impossibility of properly changing the personnel of the station force so as to avoid a repetition of the same blunder under similar conditions of nervous strain. Aside from the loss of apparatus, personal injury has sometimes resulted from a mistake in switching. From a legal standpoint it is not infrequently important to have evidence to show that damage was not due to improper switching. In one instance that comes to mind eight linemen were injured and one killed while stringing up a broken line. At some distance away there was a lightning storm. It was difficult to decide whether the fatal charge of electricity was due to the lightning, or to a mistake in switching at one of the stations, or to some local carelessness.

Where so much depends on a knowledge of switch operations it would seem that any device which makes an accurate record would give not only a good insurance against repeated acts of inability and carelessness, but would also be worth while in the training of reliability in men and in furnishing valuable evidence of conditions that any business demands.

Two experiences out of many are chosen for further illustrations. In charging an aluminum lightning arrester a very good all-round switchboard attendant decided to do his work thoroughly. He was instructed several times to charge about ten seconds, but he failed to catch the desirability of any limitation; consequently after some damage had taken place an examination was made of the record of the discharge recorder, which showed that the wear on the plates of the aluminum cells during one year was equivalent to forty years of normal service. Doing the work thoroughly meant, to him, charging the arrester for seven minutes instead of ten seconds.

In the process of manufacture of some insulating material in the factory, there were several successive steps which required exact intervals of application of electrical current, potential and heat. A man was trained to carry on this work. After he undertook the tasks independently he was checked a number of times and found reliable. From time to time certain unmistakable variations in the final product were found. The workman could give no explanation. He claimed he had conscientiously given the proper time to each application. There were good reasons for not doubting his honesty. Finally, however, it was decided to go to considerable expense to put in automatic recording devices. When occasional errors as great as fifty to one hundred per cent were subsequently found the workman was as greatly surprised as any of the rest of us. He had, apparently, occasional lapses or off-days. With the aid of the automatic recording instruments he was able to correct his lapses. The situation is now satisfactory to every one concerned.

Aside from the saving of expensive errors, the multi-recorder will have a use in diagnosing the source and growth of trouble on an electrical system. Events often follow each other in too rapid succession to be noted. Frequently an operator is not in a position to note what happens. Since the multi-recorder is more than twice as rapid in its operation as an oil switch it can follow the succession of events. Time element relays can be checked to the nearest second at every operation. Durations of accidental short circuit can be recorded. In some cases this will be of great value in forming an estimate of the possible damage that may have been done to the wires of a power line.

The multi-recorder will record when a line or feeder is alive, when it was energized, and from which end it was energized initially. This is accomplished by the use of two type-wheels or pencils. Assuming the use of the printing type, one type-wheel is connected to a contact on the feeder switch and the other is connected to a contact on an electrostatic couple which is energized by the line or feeder. If the line or feeder is kept alive by induction or by an accidental cross with another circuit the multi-recorder will continue to record the letter " R ", after the feeder switch is opened.

Other uses of the recorder will sometimes be found about a station. A load dispatcher will find a number of uses for it. The connections of the multi-recorder can be used to make the load dispatcher's dummy switchboard automatic. More rapid switching can be carried on with accuracy. The exact conditions are always before him. A check record is made of every change. If desired, signals and responses can be recorded. The starting, synchronizing, and stopping of generators, the operation of ventilating motors, auxiliary apparatus, and even changes in a fire room, may be recorded.

Looking forward somewhat into the future, there is a growing demand for knowledge of the mental characteristics of the men who have functions made important by the reliability that is required under all conditions of surroundings and mental fatigue. No subtle psychological tests have to be imagined to determine these mental characteristics. What is needed is an actual switchboard not connected to the power circuit but used in conjunction with the multi-recorder. Tests are to be made when the mind of the man is fresh and clear after a night of rest, and again when it is fatigued at the end of a day of exhausting labor, and then again, perhaps, after " a night off with the boys." Imitations of various accidental conditions can be reproduced by explosions and pyrotechnics, and the accuracy and time of response to these impulses can be measured by the multi-recorder. To give these tests the seriousness and nervous strain attending actual operating conditions, several other things are available. One factor might be certain mental stresses that can be caused by the presence of unusual and important witnesses. There are a number of things involving the element of surprise, which need not be reviewed here. It would be absurd to lay out rules for methods that have not yet been tried and tested. The end sought in each case will have everything to do with the choice of method and procedure.

It must be conceded that no set of tests will give absolutely positive proof that the results will indicate the choice of an unerring switchboard attendant, although they may come very near doing it. The methods will, however, eliminate immediately the applicants for such positions who have qualities of mind which entirely unfit them for the particular occupation of switching.

The choice, as the matter stands to-day, is left much to haphazard chance. The blunders which eliminate a man from the field of station attendant are very expensive. The ease with which blunders can be covered up, and the importance of doing so to the man who makes them, leaves the engineer in charge in a vulnerable position. If one could learn even of all the blunders that resulted in nothing serious, a good basis would be formed on which to judge an attendant's abilities. The multi-recorder will give a great deal of this kind of information. With a full set of tabulated and type-written accidental conditions which can happen to an electric system, taken in connection with the test switchboard referred to above, it is possible, after choosing men, to give them an extensive training in meeting promptly important situations which come infrequently to any one man.

Application of the Multi-Recorder to Theoretical Investigations. There are a number of important investigations on electrical circuits which require numerous accurate time records. One of the most important of these is the determination of the value of the overhead ground wire. Lightning storms move variably across and along transmission lines. Succeeding strokes produce punctures on spark-test papers which are superimposed and cause hopeless confusion in the interpretation of the results. One multi-recorder takes the place of thirty observers and it is more rapid and accurate. The salaries of thirty men for one day would pay a high rate of interest and depreciation on the multi-recorder for an entire year. With the necessary auxiliary apparatus the multi-recorder makes possible studies of lightning conditions which would, otherwise, be impracticable.

The Motorman Problem. The problem of testing the characteristics of a motorman is not very different from that of the one already outlined in relation to a switchboard attendant. Aside from the regret that attends a deplorable railway accident there is a legal aspect which materially affects the returns to the stockholders. How many motormen, reliable under normal conditions, lose their judgment, accuracy, and speed of action, at a moment when human lives are suddenly endangered by the movement of electric cars under their control? The problem is not far different from the one of training chauffeurs. A method of accurate tests is not difficult to devise. Briefly, it requires the following elements: Moving pictures of specially arranged dangerous situations, fast and variably speeded vehicles suddenly appearing out of a side street and crossing or stopping on the track, confused pedestrians in various positions of danger, etc. For taking these pictures the camera is to be carried down the track in a light vehicle that can be suddenly stopped. Considerable attention must be paid to the rate of the moving film, with the conditions of subsequent reproduction in mind. Let us assume that these records are complete.

The next step is to block up a street car in a car barn and connect the motor to sufficient inertia to equal that of the car. Place a screen a few feet in front of the motorman's vestibule and place back of this screen the moving picture machine. Gear the motor through a proper ratio to the moving picture machine. Put a recorder on the brakes, bell, the several positions of the controller, velocity meter, retardation meter, and a contactor on the moving picture machine which closes the instant the dangerous condition appears. Put a motorman in the vestibule and as he runs his car down this eventful picture street, measure automatically his judgment under various trying conditions, and his accuracy and speed of mental and physical response. If he passes the pictures through a dangerous situation before he can stop his motor and the picture machine, he has had an accident. Accidents which are absolutely unpreventable will be indicated by the inability of any motorman to respond to the impulse and stop his car in time. By the use of this outfit men can be trained to meet a situation promptly. To prevent over-familiarity with the situations and the possibility of foreseeing a danger before it actually appears and prematurely preparing for it, fresh pictures of new situations can be supplied according to the need. No matter what flaws may be noted in this method, if it is applied with understanding and common sense it is possible, to say the very least, to weed out such applicants and men from the force as are inherently not adapted to this occupation.

To meet certain situations several seconds of afterthought are necessary. To reduce the time of response, most of these seconds of afterthought can be squeezed into forethought by experience. It is uneconomical to get this experience by maiming people. Everyone who has given it the least attention has noticed how actions become automatic. There is a world of illustration of this. Slip on the ice or a banana peel and a foot will shoot out quickly and recover the balance (usually) before conscious thought takes place. The fingers of a piano player and of an operator of a typewriter, move automatically to the proper positions without conscious thought or effort. If we have a complicated electrical test to make, first imagine all the possible accidents that can take place and go through phantom actions for each case to train the senses to meet the situation promptly should it occur. This is storing up afterthought in the form of forethought ready for instant use. The same quick reaction can be cultivated in the mind of a motorman by the use of the apparatus described in the foregoing paragraphs.

THE MULTI-RECORDER

Conditions existing in electrical work as outlined have suggested the necessity of a recording device which will make easily readable records of switching operations, lightning disturbances, arcing grounds, and in fact any phenomena, mechanical or electrical, which may be used to close an electrical contact.

The difficulties encountered in devising such a mechanism may not at first be apparent. The record after being made should appear comparatively simple. The first conception of what the record should be like was gained by investigating the records made by other standard recording instruments such as the recording voltmeter, the discharge recorder, etc. In these recorders the record paper is continuously drawn through the machine, usually by a direct-connected clock mechanism. In many cases this would be a waste of paper and would also make a record which could not be easily read, owing to the fact that a large amount of paper would have to be inspected before the desired indications of operation could be found. For this reason the idea of having the paper continuously moving through the instrument whether any operation was being recorded or not was abandoned and it was decided, if possible, to make the recorder move the paper in steps, the stepping to take place only when records of switching, etc., were made. It should be noted, then, that our problem is to record transitory phenomena. Many different schemes were considered as to the manner of producing a simple record. Of these, two were decided upon as being the most feasible and the easiest to read. The first consisted of a set of pencils equally spaced and bearing down on the record paper. These pencils are supported at the end of an arm extending outward from an operating armature. When anything to be recorded occurs, say closing or opening a switch, the pencil previously selected to record the operation of the switch, will move a short distance either to the right or left, perpendicular to the direction of motion of the paper, and will remain in this position as long as the switch remains open or closed. After the pencil has moved over, the paper is stepped forward a short distance and then remains at rest until a pencil is again moved by some recordable operation.

The second scheme was to provide type wheels in place of the pencils. Each wheel would have two characters cut in its rim and the operating switches would cause their corresponding wheels to be rotated so that the proper character would come in line to print. The characters chosen were *R* and *G*, corresponding to red and green as used in switching. In addition to these letters successive numerals were used. The next consideration was the printing of the time. Owing to the fact that the paper was to be stepped only when something to be recorded took place, the record paper could not have the time previously printed upon it as in the case of the record papers used in recording voltmeters, etc. Therefore, some sort of a time indication must be made on the record paper at the same time any phenomenon was recorded. As a result of investigations along this line it was decided to use a special time-printing device which consisted of a set of wheels having type cut in their rims. The question then arose as to how accurately this device should print the time. In other words, if two records were made, say one second apart,

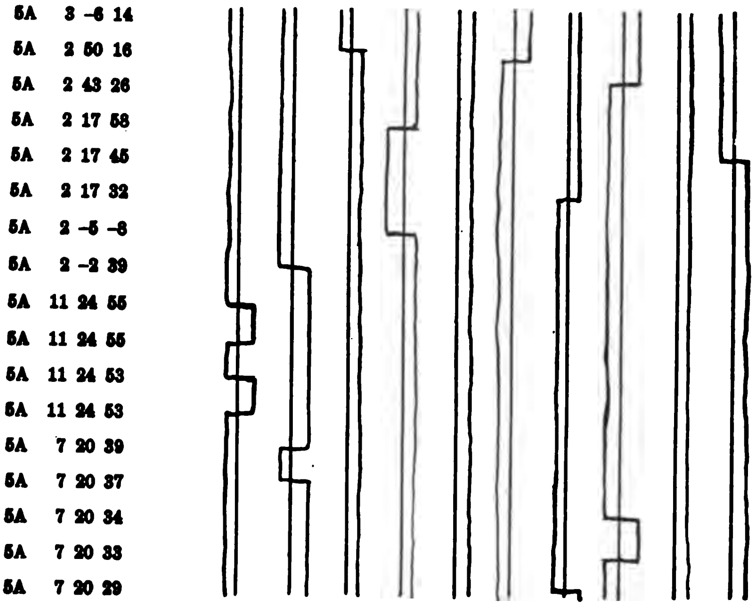
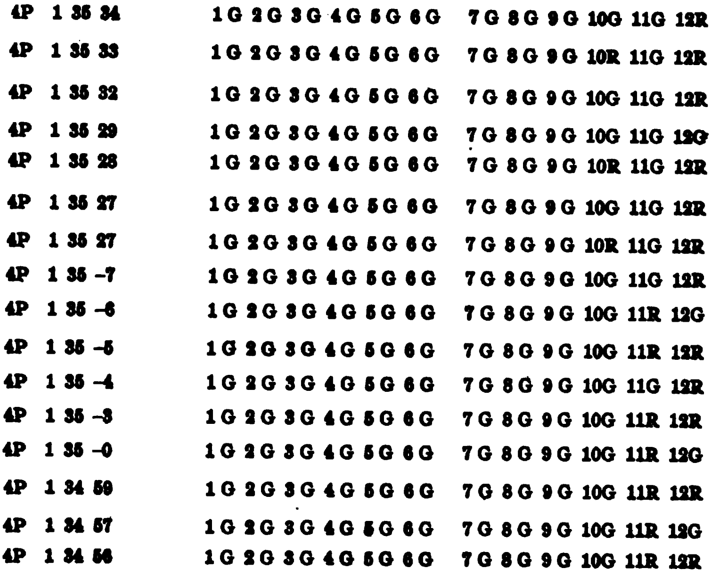


FIG. 1—RECORD OF PENCIL TYPE MULTI-RECORDER.

would it be necessary to show that the difference in time between these two records was one second, or would it be sufficient to show the approximate time of day at which the records were made? Let us take an illustration to show one of the factors which influenced the final decision: On the system consisting of a number of feeders, it is not unusual that several switches will be opened in quick succession. It is impossible to tell where the trouble started, and which switch opened first. It is desirable to have the time element sufficiently small so as to separate such phenomena.



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4P  1 35 34     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12R
4P  1 35 33     1G 2G 3G 4G 5G 6G   7G 8G 9G 10R 11G 12R
4P  1 35 32     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12R
4P  1 35 29     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12G
4P  1 35 28     1G 2G 3G 4G 5G 6G   7G 8G 9G 10R 11G 12R
4P  1 35 27     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12R
4P  1 35 27     1G 2G 3G 4G 5G 6G   7G 8G 9G 10R 11G 12R
4P  1 35 -7     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12R
4P  1 35 -6     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12G
4P  1 35 -5     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12R
4P  1 35 -4     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11G 12R
4P  1 35 -3     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12R
4P  1 35 -0     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12G
4P  1 34 59     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12R
4P  1 34 57     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12G
4P  1 34 56     1G 2G 3G 4G 5G 6G   7G 8G 9G 10G 11R 12R
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FIG. 2—RECORD OF PRINTING MULTI-RECORDER.
Changes in the recorder are made in Nos. 10, 11 and 12.

The use of two disks in place of the hour and minute hands on the clock suggested itself first, but in order to get an accurate time indication it would be necessary to have a very large disk, so large, in fact, as to be difficult to handle. Experiences with friction in such big wheels led us to believe that such a clock would be a poor time keeper, and therefore, we turned to an electrically driven clock, or a set of gear wheels. With this device it is possible to have one master clock run any number of machines, even to the extent of connecting different stations together, and in this way widen the scope of accurate record of the multi-recorder. The impulse for the electric clocks is received from a clock pendulum.

The principal parts of these multi-recorders are

1. A master clock.
2. Time-wheels for printing.
3. Record-wheels or pencils.
4. Printing mechanism consisting of a set of hammers which strike the row of type wheels.
5. The paper-advancing mechanism.
6. Outside the machine are the contacts which move when phenomena occur which it is desired to record.

A problem of the multi-recorder involves the moving of 10 to 30 distinct recording devices, which can move singly, or all at once, without interfering either with each other or with the printing mechanism. The printing mechanism must be responsive to the movement of any one recording pencil or wheel, and to any number of them operating simultaneously. Furthermore, the printing hammer must not strike the time-wheels when they are moving from one second to the next. Since we desire to record the phenomenon when it takes place, it is evident that if a phenomenon occurs at the instant the master clock ticks, the time wheels must not move. Yet the second of time in the movement of the time-wheel must not be lost. These two conditions are fulfilled, when it is necessary, by delaying briefly the movement of the time-wheels. Definitely, what takes place if the phenomenon occurs at the end, say of the eighth second, is that the time-wheel will be delayed and the eighth second will be recorded; it requires $\frac{1}{6}$ second to make the record so that $1\frac{1}{6}$ seconds later the time-wheel moves up to 9 seconds. Five-sixths of a second afterwards the time-wheel moves up to 10 seconds on exact time.

Another problem connected with this device relates to the means of recording changes that are transitory in duration. The movement of an oil switch does not fall under this designation. The occurrence of the operation of a switch is transitory, but it has a duration of at least a second before it can be followed by another movement. In other words, the switch is either against the " open " contact or the " closed " contact in a definite manner.

The recording of a lightning stroke is something quite different. It comes and is over much sooner than any mechanical device can move. In many cases it is too quick even for an oscillograph to follow. On the other hand, the problem takes a new form when the lightning strokes cause an accidental ground. Then the surges will be continual over a number of seconds or minutes. If the multi-recorder made a continuous record during all this time it would run out yards of paper uselessly.

There are other factors connected with the general phenomenon of surges, such as large and small current, high and low potential surges, as well as the frequency and duration of the surges. These factors will be taken up later in a paper on " A New Discharge Recorder." For the present it suffices to state that the device which best meets most of the imposed conditions involves the use of a specially constructed coherer. A surge of the shortest possible duration will cohere the coherer. The device is so arranged that the coherer remains cohered until the record is made. There is then a movement to de-cohere. If, however, the surges are continuous a second coherer in parallel with the first prevents the decoherence and no further record is made by the multi-recorder until the surges cease. It is seen from this description that the multi-recorder will record the duration of charging an aluminum arrester.

MECHANICAL DETAILS

The illustration of the multi-recorder, Fig. 5, shows the mounting of the relays and the terminal board. All wires leading from the multi-recorder are carried downward through the cast-iron pedestal shown in the illustration. The magnets for operating the record type-wheels are situated just in front of the terminal board and their armatures are pivoted to move vertically forward and backward. Brass links connect the upper parts of the armatures to lugs on the recording type-wheels which are shifted forward or backward by the movement of the armatures. The time-printing type wheels are constructed very similar to an ordinary consecutive numbering stamp, and they are mounted so that they may be easily reset. The paper roll is mounted near the center of the recorder and the paper passes under the type wheels, then between two rollers which step it through the space between the hammers and the type wheels. A carbon paper roll, the same width as the record paper, is mounted just above the record paper roll and this is passed between the type and the record paper. The carbon paper is rerolled upon a spool just in front of and above the type wheels. This spool is driven by a small chain running over a sprocket wheel fastened to the paper-advancing rollers. See Fig. 6. The printing solenoid is located under the paper-advancing rollers, and padded hammers linked to the core of the solenoid *P* (Figs. 3 and 7) are made to swing upward, striking the underside of the record paper, and causing the type to make a carbon imprint upon the record paper. When the core is released it is returned by a strong spring which also rotates the advancing rollers and moves the paper, as before mentioned. The stepping is accomplished by a pawl and ratchet mechanism.

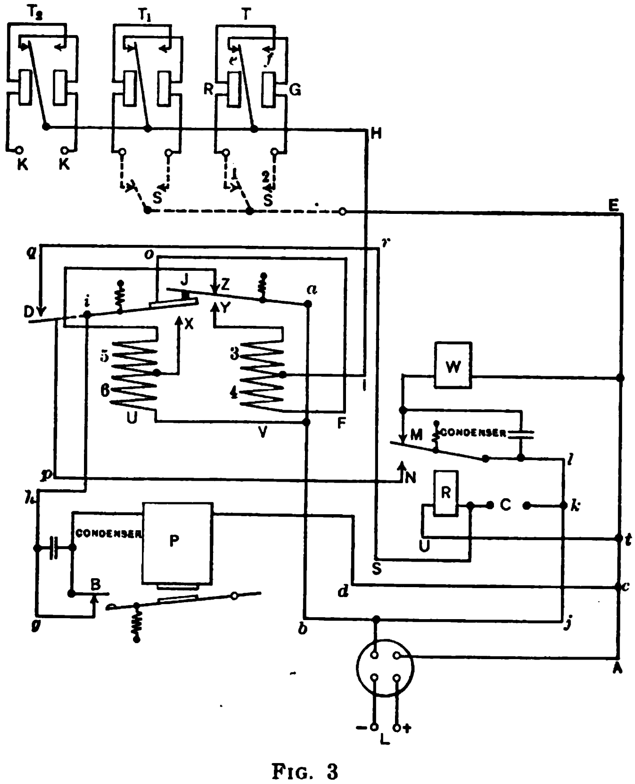


FIG. 3

With respect to size, there is practically no difference between the two types of recorders and in fact they look very similar. Nearly all the metal frame work is made of finished brass. The machines are mounted on a slate or marble slab supported by a cast iron pedestal. The recorder is provided with a glass case having a hinged top. This renders the machine free from dust and at the same time makes it easily accessible.

Almost any part of the mechanism may be viewed through the encasing glass. The record paper feeds out under the lower front edge of the case, and it is provided with a straight edge so that portions of the record may be torn off.

Wiring. Now that we have described the functions of the multi-recorder in general, more detailed description of the wiring between the electromagnets and interlocking contacts will be given for those who wish to follow more minutely the method of operation.

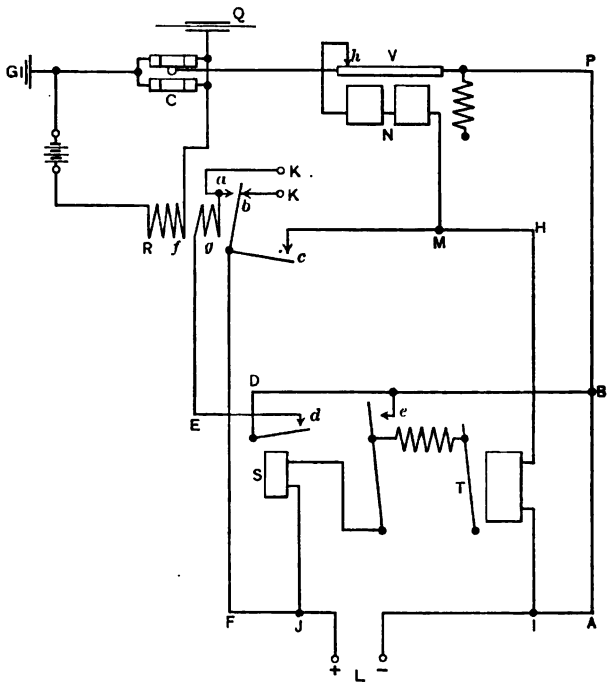


FIG. 4

In this part of the paper it is the purpose of the writers to describe as briefly as possible the two types of multi-recorders which have been built and which operate successfully. The recorders will be referred to as multiple-connected and series-connected. Both recorders are very similar in construction, with the exception that the series-connected recorder makes use of a moving element which makes a pencil line record, while the multiple-connected machine makes a type-printed record of all switching operations, etc.. The writers are indebted to Mr. A. H. Davis, of the Lightning Arrester Laboratory, for this series connection. References to Fig. 1 and Fig. 2 will show wherein the records differ. It will be noted that in each record the time is printed to the second, *i.e.*, 2A6 44–3 is to be interpreted thus, Monday, a.m., 6th hour, 44th minute, third second. In Fig. 1 let us assume that line No. 1 is a line which is to show the operation of the switch. The paper strip used for this record has parallel colored lines in sections of five, drawn the length of the paper. Each of these lines is a center line upon either side of which the recorder draws its record line. The center lines are colored so that the records may be more easily read. Whenever line No. 1 is at the left of the center line, the indication is that the corresponding switch is open. The point at which line No. 1 crosses its center line shows the time when the switch was operated. Whenever line No. 1 is at the right of its center line the indication is that the switch is closed. Records of other operations are similarly shown.

In Fig. 2 the operation of the switch is indicated by the printed number and letter, *i.e.*, 1*G* indicates that the switch is open—1*R*, that it is closed. The time at which the switch operates is shown opposite the record print and at the left of it.

Let us now take the multiple-connected recorder and go through with its principles of operation. This recorder may be designed to operate satisfactorily on any direct-current circuit of from 15 to 120 volts. If the recorder is to be operated on a voltage higher than 120 it would be desirable to put resistance in the various circuits to limit the current. Fig. 3 shows the connection for the low-voltage type. S (S_1 to S_{30}) represents the contacts which are operated by the switching or similar operations that are to be recorded. R and G are the magnets which turn the type-wheels that print the record. T (T_1 T_2 to T_{30}, at the top of the figure) is a special quick break contact mechanism which is tied to the armature of R and G by means of a toggle spring (not shown in the diagram). This mechanism and its contacts, e and f, are placed at the top of the recorder and may be seen in the accompanying illustration (Fig. 5). V is a relay coil having a high-resistance winding (4) and low-resistance winding (3). U is a relay coil having winding similar to V, 5 being the low-resistance winding and 6 the high. P is the printing and paper-stepping solenoid.

Let us now go through with an example of the operation of

[CREIGHTON, NICHOLS AND HOSEGOOD]
FIG. 5—BACK VIEW OF THE PRINTING MULTI-RECORDER.

[CREIGHTON, NICHOLS AND HOSEGOOD]
FIG. 8—BACK VIEW OF THE PENCIL TYPE OF MULTI-RECORDER.

[CREIGHTON, NICHOLS AND HOSEGOOD
FIG. 6—FRONT VIEW OF THE PRINTING MULTI-RECORDER.

[CREIGHTON, NICHOLS AND HOSEGOOD]
FIG. 9—FRONT VIEW OF THE PENCIL TYPE MULTI-RECORDER.

this recorder. Suppose we select an oil switch that has been connected to operate the contacts S of this recorder. These contacts, S, may be mechanically fastened to the switch, or S may be a three-point relay connected in the control circuit so that the contact 2 is closed and contact 1 open when the green light is on, and contact 1 is closed, and 2 open, when the red light is on. Assume that the oil switch is about to be opened; the previous closing of the oil switch had broken the contact 2 and closed the contact 1 of S as shown. Also it had broken contact f and closed contact e of the quick break contact T. The oil switch opens, breaks contact 1 and makes contact 2 at S. This allows the current to flow from line L, shown at the bottom of the figure, toward the right through the connecting wire AE to the contact 2 at S, through magnet G and contact e of T down through wire HI, through the high-resistance coil 4 of relay V, through wire Fo, contact J, wire $a\ b$, back to the line L. The current which flows through this circuit is too small to cause the armature of G to move, and, therefore, the circuit through e at T remains unbroken. This current is, however, sufficiently strong to cause coil 4 of relay V to draw its armature against contact Y and mechanically close contact X. During this movement contact J is not broken and it remains closed until contact Y is open, while contact X remains closed. As soon as contact Y is closed the current is free to pass through the low-resistance coil 3 of relay V, and since the current is now much larger, due to the lowering of the resistance of the circuit, the magnet G moves its armature and the type wheels linked to it (not shown in the figure). The motion of this armature also breaks the circuit at contact e of T, and closes contact f of T. This puts the contacts of S and T in relative positions at rest. It may readily be seen that the contact J is necessary in order that the second phenomenon may not interfere with recording the first. If, however, two or more phenomena should occur simultaneously or nearly so, records of all the phenomena will be made in one operation of the recorder. It should be noted that in breaking contacts J and Y, the common connection $I\,H$ for all the operating contacts, e and f, of T ($T_1 T_2$ to T_{30}) is open-circuited at Y and J, so that should another phenomenon occur while contact J is open (contact J cannot be opened without opening contact Y), the entire operation of the recorder for this new phenomenon will not take place until the first record just being described has been finished. The current which operates *G* also holds contact *Y* of the relay *V* closed until the circuit is broken at contact *e* of *T*, when relay *V* is de-energized, contacts *Y* and *J* are opened, and contact *Z* is closed by a spring return. When the armature *V* is returned to make contact *Z*, contact *X* of relay *U* is held closed by the current which flows from the line *L* through wire *A c d*, printing magnet *P*, contact *B*, wire *g h i*, contact *X*, the high-resistance coil 6 of *U* through wire *b*, back to the line *L*. This current is too small to operate the printing and stepping magnet *P* but is sufficiently large to cause relay *U* to hold contact *X* closed. At once the contact is made at *Z*, the current flows through the path from line *L* through wire *A c d*, printing solenoid *P*, contact *B*, wire *g h i*, contact *X*, low-resistance coil 5 of *U*, upward through contact *Z*, and downward through wire *a b*, back to the line *L*, and operates the printing solenoid *P*. Closing the circuit of solenoid *P* on operating current throws a set of hammers against the type wheels, thus making the printed record. When the stroke of solenoid *P* has reached its limit the circuit is automatically opened at contact *B*, and relay *U*, losing its energy, allows contact *X* to be opened by a spring on its armature, which also closes contact *J* as in the original position. The opening of contact *B* is purely a mechanical operation and is accomplished by the core in solenoid *P* reaching its limiting position. Solenoid *P* being also de-energized by the breaking of contact *B* releases its core and it is returned by a strong spring which steps the paper along for about a quarter of an inch. The above cycle of operation having been passed through, it will be seen that every part of the recorder is back to its original position and the recorder is now ready for the next record. Should two or more switches be operated simultaneously, a corresponding number of recording type wheels would be moved. For example —if S and S_1 should close their contacts 2 (or 1) at the same time, then the coils *G* (or *R*) of T and T_1 would be thrown in the circuit in parallel. They would move their corresponding type wheels simultaneously when their circuits were made to carry sufficient current to operate them, and relay *V* would close its contact *Y*. The relation between the resistances of coils 3 and 4 of relay *V* is so proportioned that any number of records may be made simultaneously.

The time-printing type wheels are operated by a solenoid whose circuit is closed and opened by a relay of the clock circuit. A clock beating seconds has attached to its pendulum a pair of simple contacts (not shown in figure) which are connected to *C* in the diagram of Fig. 3. When the clock ticks the circuit of relay *R* is closed, opening the circuit of the type-wheel solenoid *W* at contact *M*, which allows the advancing pawls of the type-wheel mechanism to be stepped backward by a spring. When the clock circuit is opened, then the relay *R* is released and the circuit of *W* is closed at contact *M*, which advances the pawls on the type-wheels, moving them forward and causing the wheels to advance one second. The above cycle is repeated every second. Should a switching operation take place at such a time that the printing would occur just as the time-printing wheels were advancing, it would not be possible to read the time on account of the failure to print properly, as before mentioned.

This possible failure of the recorder is eliminated by contact *D*, which is in a circuit in parallel with the clock circuit. Normally, when switching occurs with contact *N* open the contact *D* has no function; but should the contact *N* be in a closed position at the time that relay *U* closes (which closes contact *D* as well as contact *X*), contact *D* would complete the circuit of the clock relay *R* through contact *N* and prevent the spring from opening *N* when the clock contact opened.

This circuit may be traced as follows. Starting from line *L* the current passes through the wire *A t U*, relay *R*, wire *S r q*, contact *D*, downward through wire *p*, contact *N*, wire *l j*, back to line *L*. Normally, when the recorder is not operating, the circuit when the clock contact closes is as follows: Current flows from line *L* through wire *A t U*, relay *R*, clock contact *C*, wire *k j*, back to line *L*. The ticking of the clock then opens and closes contacts *M* and *N* alternately, closing *M* causing the time wheels to be moved, and closing *N* making it possible for contact *D* to prevent the opening of relay *R* when the movement of time wheels is to be delayed. Relay *R* will, however, be opened when both contact *D* and the clock contact are opened, since this opens the circuit of relay *R*. It must be understood that this delaying of the movement of the type-wheels is only a fraction of a second, and does not therefore throw the time of the wheels behind that of the clock.

RECORDING OF LIGHTNING DISTURBANCES AND SURGES

Reference to Fig. 4 will show the connection of the apparatus used to operate the recorder for high-frequency disturbances on the transmission line, previously referred to in this paper. *Q* is a condenser connected between the transmission line and the special coherer *C*, which is connected to ground as shown. *V* is the tapper which decoheres coherer *C*. *R* is a relay which may be closed only by current in the coherer circuit. *T* is a time limit relay to close the circuit of the relay *S*. *L* is the source of direct-current power to operate the mechanism, which is the same source as shown in Fig. 3. The terminal *KK* should be connected to the corresponding points lettered *KK* in Fig. 3 of the multi-recorder.

The operation of the discharge recorder is as follows: High frequency coheres coherer *C* and energizes relay coil *f* of *R*, opening contact *b* and closing contacts *a* and *c*. Closing contact *a* performs the same function as one of the contacts (1) of *S* in Fig. 3 and causes the recorder to print the exact time at which the disturbance commenced, and also printing the letter *R* which will indicate that the disturbance is on the transmission line. Contact *a* also closes the circuit of the holding coil *g* of relay *R* as follows: Current flows from line *L* through wire *A B D*, contact *d* (which is normally closed), wire *E*, coil *g*, contact *a*, downward through wire *F* back to line *L*. When relay *R* operates, contact *c* closes a circuit as follows: Current from line *L* flows through wire *F* upward through contact *c*, wire *H*, downward through the coil of time limit relay *T*, through wire *I* back to line *L*. The time limit relay *T* operates about a quarter of a second after contact *c* has closed, and closes contact *e*. The circuit through contact *e* is as follows: Current flows from line *L* through wire *A B*, through contact *e*, relay *S*, wire *J* back to line *L*. The relay *S* opens contact *d*, and therefore causes coil *g* of relay *R* to lose its energy. Contact *c* also closes the circuit of the tapper coils of *V* as follows: Current from line *L* flows through wire *F*, upward through contact *c*, wire *M N*, the coils of *V*, contact *h*, wire *P A*, back to line *L*. The armature of *V* will now vibrate like the armature of an electric bell and the hammer at the left end of the armature will tap the coherer tubes *C* alternately and decohere them. The coherers *C* in turn will break the circuit of coil *f* in relay *R* as soon as the high-frequency disturbance on the transmission line has ceased.

If the disturbance is of very short duration (less than a quarter of a second) coil *f* of relay *R* will at once lose its energy as just explained, but the armature of relay *R* will not be released until the time relay *T* has operated relay *S* and broken the circuit of the holding coil *g* of relay *R* at contact *d*. This, then, will delay the breaking of contacts *a* and *c* and consequently the making of contact *b* which would be accomplished by the spring on the armature of relay *R*. Delaying the breaking of contact *a* and the making of contact *b* is necessary in order that the recorder (which is operated by closing contact *a* or *b* as before explained) will have time to go through its first cycle of operation which will make an *R* record, before contact *b* is closed, which in turn would again cause the recorder to operate but this time it would make a *G* record. Should the contact *b* be closed too soon the recorder might not complete its first record and, therefore, no disturbance would be indicated on the record sheet. Now, if the disturbance is of long duration (several seconds or minutes) the coherer will be kept cohered and coil *f* of relay *R* will hold contacts *a* and *c* closed even after relay *S* opens the holding coil circuit *g* at *d*. The recorder, as before stated, has printed the letter *R* on the record sheet, together with the time at which the disturbance commenced. When the disturbance ceases, coil *f* of relay *R* loses its energy and contacts *a* and *c* open. When contact *a* is opened and *b* closed, the particular record type-wheel recording the above phenomena is shifted so that it will print *G* instead of *R* and also the time at which the disturbance ceased. The time of duration of the disturbance can be easily seen by noting the difference in time of these two records.

Incidentally, this last operation would prove very valuable in connection with the charging of electrolytic lightning arresters. The time at which the charging was done would be recorded, and also the duration of each charge would be shown.

It will be seen from Fig. 3, and the previous reference to it, that a magnet *R* or *G* must operate and turn its type-wheel before the printing can take place and that the whole network is so devised that each operation must come in its regular order.

As before mentioned, the two recorders are very similar in mechanical construction. The essential differences between the two are in the electrical principles, and, in this particular case, in the fact that the series-connected recorder has been provided with pencils instead of type wheels. However, it is possible to design either recorder with pencils or type wheels.

In the illustration, Fig. 9, the arrangement of the pencil-operating magnets may be seen.

We will now consider the electrical connections and operation of the series-connected recorder. Fig. 7 shows the diagram of connections.

It will be noted that all the magnet coils *R* and *G* are connected in series, and the operation of the pencils depends upon the short-circuiting of either coil *R* or *G*. *S* shows the contacts of a six-point relay which is operated by the switching, the same as in the multiple-connected recorder. *U V* is a relay having a double winding, as shown. *X Y* is a two-coil relay, each magnet of which operates upon the same armature. *Z* is an electrically operated mechanical interlock which locks the pencil bars when they are at rest. This interlock consists of

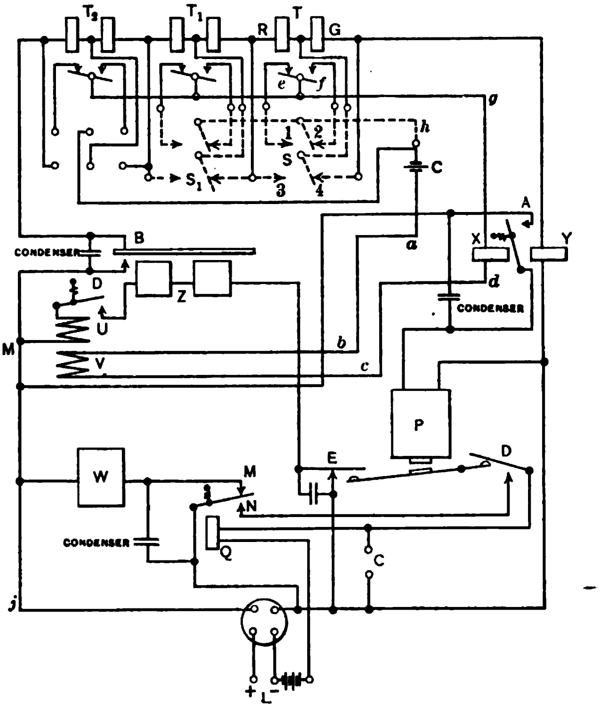


FIG. 7

an electrically operated bar having upon its lower edge a number of V-shaped projections which normally rest against similar projections extending upward from extension of the pencil magnet armatures. The points of the V projections on the armatures will be on one side or the other of the projections on the interlocking bar and the pencils may not be moved except when the interlocking bar is raised.

When an oil switch is closed, one of the six-point relays

S operates so that contacts 2 and 4 are opened and contacts 1 and 3 are closed. Consider, first, the closing of contact 1. The circuit from the low-voltage battery *C* shown in this line, is completed through contact 1 as follows: Current flows from battery *C* through wire *a b*, operating coil *V* of relay *M*, through wire *c d*, through coil *X*, wire *g*, contact *e* of *T*, through contact 1 of *S*, back to the battery *C* through wire *h*. Current in coil *X* prevents the closing of contact *A* when coil *Y* is energized. Current in coil *V* closes contact *D*, which completes the circuit of relay *Z* to line *L*, as follows: Current flows from line *L* upward through contact *E*, through wire *i*, the coils of relay *Z*, through contact *D* of relay *M*, downward through wire *j* back to line *L*. Relay *Z* closes contact *B* and also mechanically unlocks the pencils so that they are now free to be moved by their magnets *R* or *G*. The pencils are kept locked in place because the paper moving under the pencils might pull them out of place should they be free to move. Closing contact *B* sends current through all coils *R* or *G* in series which are not short-circuited by the contacts 3 or 4 at *S*. In this case, coil *R* is short-circuited by contact 3. Therefore, the current energizes magnet *G* and its armature moves, pulling the pencil to the right, opening contact *e* and closing contact *f*. Breaking contact *e* opens the circuit of coils *X* and *V*. De-energizing *V* does not break contact *D*, as the relay is held closed by the holding coil *U*. De-energizing *X* permits relay *Y* to close contact *A*, which completes the circuit from the line *L* through the printing and stepping solenoid *P*. The printing takes place the same as in the case of the multiple-connected recorder (except that the only part of the record which prints is, obviously, the time) and the circuit of coils *Z* and *V* is opened at *E*; their armatures are released, breaking contacts *D* and *E*. Opening contact *B* opens the circuit of coil *Y*, which in turn releases its armature and opens contact *A*; this breaks the circuit of the printing solenoid *P*, its core is released and the paper-advancing rollers are moved, the same as described in the other recorder. The clock mechanism and connections are substantially the same in both recorders, and the diagram of connections may be seen in Fig. 3 or Fig. 7.

The discharge recorder terminals *K K* of Fig. 4 should be connected to the operating coil of one of the six-point relays, *S* (S_1, S_2, to S_{30}).

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

STUDIES OF PROTECTION AND PROTECTIVE APPARATUS FOR ELECTRIC RAILWAYS

BY E. E. F. CREIGHTON, F. R. SHAVOR AND R. P. CLARK

The object of this paper is several-fold, first, to describe the effects of high frequencies on car wiring; second, to describe experiences with the application of the aluminum arresters to an electrical railway where lightning is especially severe; third, to describe additional devices applied to the d-c. aluminum arrester which give it greatly diminished deterioration with only a slight decrease in protective value; and, fourth, to describe experiments on the extinguishment of d-c. arcs and the changes that have resulted in the redesign of the old magnetic blow-out arrester.

General. Some of the main points of past standard practise in the protection of railway apparatus and lines might to advantage be briefly summarized as a beginning. Cars using direct current are protected by one or two arresters of the series gap type, and a choke coil. To diminish the strains on the car arresters and apparatus, arresters are placed along the line in greater or less number, according to the type of arresters and the severity of lightning storms in the locality. These arresters are all of the series gap type. In fact, with the exception of the d-c. aluminum arrester, there is none that could be dignified by the name of " arrester," that has not a gap in series.

All of these standard arresters contain more or less internal series resistance. Since, in a d-c. circuit, dynamic current must always follow the lightning spark across the gap of the arrester, another distinguishing feature is the method employed in extinguishing the arc in the arrester.

In the older type the dynamic current energizes an electromagnet which produces a magnetic field perpendicular to the arc and thus drives it up a porcelain arc-chute. The elongation of the arc increases its resistance, which reduces the current gradually until the arc is extinguished. This takes place when the energy of the arc is reduced to a value such that the rate of cooling makes it unstable. All this takes a measurable amount of time. In order that no serious damage shall be done to the electrodes of the gap during this time, some series resistance is necessary to limit the value of current. The series resistance is required also to furnish potential for the electromagnet. Since this resistance is in the path of the lightning, the best design of arrester is the one which reduces the resistance to the minimum value without jeopardizing the life of the arrester by the destructive action of the dynamic current.

A second type of gap arrester prevents the continuance of the dynamic arc by an automatically variable series resistance which has a very high value to direct currents at 600 volts. It has a lesser resistance and impedance at higher potentials and high frequencies.

As protectors, the efficiencies of both of these arresters are limited not only by the active values of resistance but also by the presence of the series gap. The detrimental effect of the gap is reduced to a minimum by the well known application of the lightning choke coil.

The efficiency of the " gap-resistance " type varies according to the design, and they have usually proven sufficiently satisfactory, in all but extremely severe lightning districts, to warrant their standardization.

A third type of arrester gap uses an electromagnet in parallel with a resistance, but the arc is interrupted by the mechanical movement of a plunger. This type has its application confined mostly to overhead trolley lines.

It seems unnecessary to review the varied conditions of demand for protection according to the geographical location, also the variations in demand along any particular line which is more or less overshadowed by trees and houses, as these matters are common knowledge.

THE RELATION OF CAR WIRING TO PROTECTION

As far as the writers know, very little attention has been paid to the matter of car wiring from the standpoint of protection. In many cases the wiring is such as to jeopardize the insulation of the motors and other electrical car apparatus in spite of the application of the best lightning arresters. This objectionable condition consists in placing the trolley bus wire and the ground wire in the same cable with the controller wires of the motor. When a lightning charge comes down the trolley, a portion of it passes by induction from the trolley cable directly into the car controller cables of the motor and thence into the motor. An instant later the charge passes around the wiring to the motor, but the first stroke on the insulation of the motor comes from the bus wire in the cable. Where the charge is forced to follow the wiring it is possible to retard it for an instant by means of a choke coil, and thereby give the lightning arrester an opportunity to carry it off directly to ground. But when the charge is permitted to pass directly into the motor winding by induction the protective value of the arrester is not brought into play. Even the aluminum arrester with unusually short connections is placed at a great disadvantage, and the gap type arresters with their spark potentials of 2000 volts to 3000 volts and their dielectric spark-lags are utilized at a minimum of their effectiveness. Before going into this subject further, some isolated experiments illustrating the effect of induction will be given.

EXPERIMENTS IN HIGH-FREQUENCY INDUCTION BETWEEN PARALLEL WIRES TO INDICATE THE RELATION OF CAR WIRING TO PROTECTION

The possibility of a lightning stroke being induced between wires on a car and thus by-passing the protection given by a lightning arrester, prompted an experimental investigation of this subject. The available space on a car is so limited that wires are generally grouped in a cable, and this condition is the most favorable to the inducing of potentials at frequencies approximating lightning frequencies. The first tests were made to determine the values of induced potentials.

Referring to Fig. 1, a large static machine with condensers consisting of four ordinary one-gallon leyden jars attached to each side of the machine was used as a source of potential for a number of these tests. The frequency of discharge was approximately 1,000,000 to 2,000,000 cycles per second, depending upon the size of the circuit and conductors used.

For the first test, two rubber-covered stranded No. 6 B. & S. cables, each 6 ft. long, were laid parallel on a table. The cable *O P* was connected across the leyden jar terminals as shown in Fig. 1, and cable *x y* had a needle gap connected across its terminals. The area *x y Q* was maintained fairly constant for all positions of test. The length of leads to needle gap was 8 ft. (2.4 m.). The distance *D* between conductors was varied and the values of *Q* at which a discharge just fails to pass at the gap *Q* were observed and recorded. The machine terminal gap spacing (*G* gap) was maintained constant at 5 in. (12.7 cm.), as this setting gave the largest value of *Q* gap for any constant value of distance *D*.

The values of induced potentials were first measured at *Q* for the wires unprotected by iron pipes. Subsequently the tests were repeated with either wire enclosed in a 1 in. (2.5 cm.) iron conduit pipe and finally with both wires in separate iron conduit pipes.

The values obtained as noted in the following tables prove that an iron pipe around a conductor does not appreciably shield it from the effects of induction under certain conditions. In fact the induced potentials are so nearly the same for the four different conditions tested that it seemed reasonable to suspect that the area enclosed by the secondary circuit is an important factor. To check this point the following test was made.

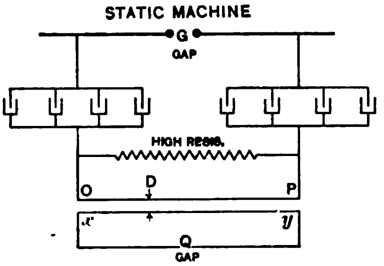


FIG. 1

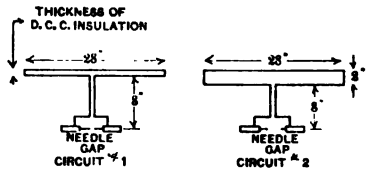


FIG. 2

Two secondary circuits were made up, each of the No. 12 B. & S. solid cotton-covered wire. The first one was made to include the smallest possible area.

This enclosed area was less than $\frac{1}{2}$ sq. in. (6.2 sq. cm.), not including the area near the needle gap, which was about 8 in. (20.3 cm.) from the primary circuit. The potential induced in this secondary circuit was not measurable on a fine needle gap.

The other secondary circuit was made to include about 56 sq.

in. (361 sq. cm.). The dimensions are shown in Fig. 2. When this circuit was tested in the same position as the first the induced potential just failed to jump a needle gap setting of 0.035 in. (0.889 mm.)

Electromagnetic Induction between Parallel Lines, 6 ft. (1.8 m.) long, "G" Gap = 5 in. (12.7 cm.)

No iron pipe used		Iron pipe on cable *x y*	
Average *D*, in.	*Q*, in.	Average *D*, in.	*Q*, in.
0.4	0.35	together	0.33
1	0.31	2	0.24
2	0.26	4	0.19
3	0.22	6	0.15
4	0.20	9	0.12
5	0.18	16	0.09
6	0.16	22	0.06
7	0.15	30	0.025
9	0.12		
12	0.11		
16	0.10		
22	0.09		
30	0.05		

Iron pipe on cable *OP*		Iron pipe on both cables	
Average *D*, in.	*Q*, in.	Average *D*, in.	*Q*, in.
together	0.31	together	0.27
2	0.25	2	0.25
4	0.17	4	0.19
6	0.15	6	0.14
9	0.13	9	0.12
16	0.10	16	0.08
22	0.03	22	0.03
30	0.025	30	0.015

Comments on Electromagnetic Induction in Car Wiring. In order to have electromagnetic induction between two parallel circuits a current in one circuit, at least, is necessary. If lightning is to cause, by electromagnetic induction, a dangerous potential in the apparatus on cars, it is necessary to find a circuit suitable for the passage of high-frequency current. Very high frequency current cannot pass around the turns of armatures, field coils, or electromagnets, since the inductance of these devices would destroy the high frequency.

If we are to find electromagnetic induction between parallel wires of the car wiring we must look for the completion of the circuit from trolley to rail in some other path than the path taken by the direct current that operates the motors. Assume that a wire is carried from the trolley to a point underneath the car at one end, designated for convenience as the No. 1 end, and then parallels the controlling wires of the motors to the No. 2 end. In order that electromagnetic induction shall take place, the lightning current must flow out the No. 2 end of this bus. If an aluminum arrester is improperly placed between the No. 2 end of this bus and ground, the lightning has a free path through the bus to ground and motors will receive a severe induced electromagnetic strain derived from the wires parallel to this bus. In fact, under this objectionable condition, the better the lightning arrester the higher the induced potential applied to the insulation of the motors. A poor lightning arrester containing considerable resistance in series will limit the strain from the electromagnetic induction, although in doing it, it will throw strains directly on the end turns of the motor connections. The cure for this trouble evidently is to avoid any connection which permits the lightning current to parallel closely the controller cables.

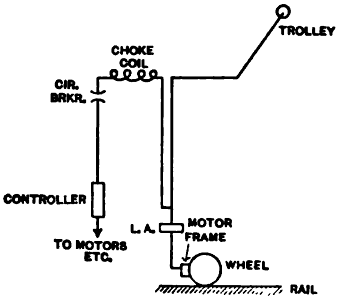


FIG. 3

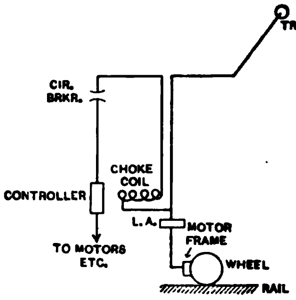


FIG. 4

Eliminating, then, the lightning arrester from this objectionable location, what other possible path is there for lightning from the No. 2 end of the bus to ground? The only answer seems to be, electrostatic capacity to ground of the circuits beyond the No. 2 end. Some idea of the possible danger from this source may be gleaned from the experiments on electrostatic induction which will be given farther on. In closing this paragraph it is desired to caution engineers who lay out car-wiring, and repairmen who change it, to avoid placing wires in such positions that electromagnetic induction from lightning can take place.

The precaution may be put in the form of a brief rule: Avoid placing any wire that carries lightning current near and parallel, for any considerable length, to any of the wiring where damage can be done by an induced charge. Aside from the illustration of the bus wire already given, this rule may mean, specifically, to avoid carrying a lightning arrester connection, which very properly extends from the roof of a car to an arrester situated near the floor of the car, directly back on itself to the top of the car to a circuit breaker or other connection to the apparatus. The wiring shown in Fig. 3 is not so objectionable as that shown in Fig. 4, where the lightning choke coil is shunted out of full effectiveness by induction between the parallel wires leading into and away from it. The most desirable connection of the lightning arrester and choke coil is shown in Fig. 5, where the parallel rising wire is carried several feet away from the connection to the arrester. The connection shown in Fig. 6 is not quite so effective as the one shown previously in Fig. 5, due to the greater length of wire in the arrester circuit. If it seems necessary to use the connection of Fig. 6, the arrester may be placed on the roof of the car, in the vestibule, or under the car, without affecting the inductance of the circuit of the arrester. When such a connection is used, however, a larger choke coil than in Fig. 5 is necessary to offset the greater inductance of the circuit of the arrester.

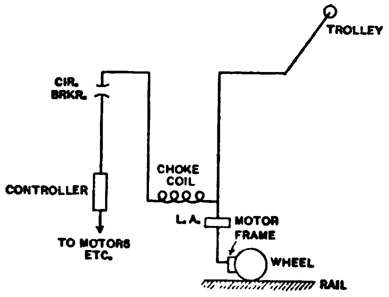


FIG. 5

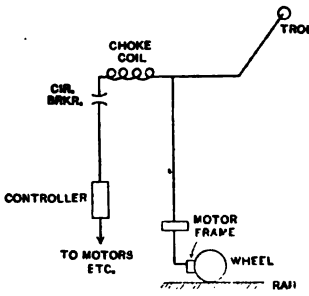


FIG. 6

Electrostatic Induction in Car Wiring. In order to make the inquiry complete the subject of electrostatic induction should be considered. As a simple case assume that in Fig. 4 there is a lightning arrester of high internal resistance, or assume that there is no lightning arrester in a circuit of this form. When a high-frequency wave comes down the vertical wire it is impeded by the choke coil and a high potential is produced between the parallel wires. An electrostatic charge in the form of a condenser charge or displacement current passes from one of these parallel wires to the other, thus shunting the choke coil. The quantity of electricity in this charge depends directly on the electrostatic capacity between the wires and the potential difference between the wires. Can this small charge do any harm? It can under certain conditions. Much depends on the electrostatic capacity of the circuit beyond the parallel wires. If, for example, the capacity of the wiring is ten times the capacity of the parallel wires, then the potential of this wiring due to a lightning stroke will be only a tenth as great as the potential across the condenser formed by the parallel wires. If the wiring beyond the parallel wires, as is more likely, has a capacity more nearly approaching the value of the parallel wires, the danger is correspondingly greater.

If the potential between the parallel wires reaches a value sufficient to puncture the insulation then, of course, the whole lightning charge goes directly into the apparatus of the car without intervention from the choke coil. Furthermore, such a shunting of the choke coil will cause no burning at the point of discharge, as the dynamic current will not follow the lightning puncture between the parallel wires, and there will be nothing to indicate to an inspector that the protection of the car has been materially weakened. A very simple rule to follow to avoid such a condition is: never bring wires connected to the opposite terminals of a lightning choke coil within, say, a foot (30 cm.) of each other. Electrostatic induction in car wiring is so easy to avoid that it is only necessary to call attention to the necessity of observing the possibilities of the occurrence of the phenomenon.

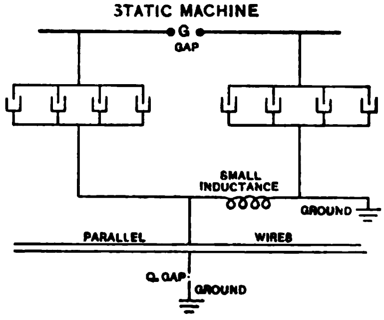


FIG. 7

Experiments with Electrostatic Induction in Car Wiring. A test intended to show the intensity of electrostatic induction between medium lengths of parallel wires, without the intervention of electromagnetic induction, is illustrated in Fig. 7. As a source of high frequency an electrostatic machine connected to leyden jars is used. The gap *G* of the machine determines the value of potential applied to the jars. On the right-hand side, the jars are shown grounded, and on the left-hand side the leyden jars are shown connected to 30 feet (9.14 m.) of straight wire; the middle point of this wire is connected through a small choke coil to the ground. A second straight wire is laid parallel and close to the first-mentioned wire, as shown in the figure, and this isolated wire is connected to the ground through a needle gap marked *Q*. For any given length of straight wire it is intended to determine the relations of the potentials at the gap *G*, which represents the intensity of the lightning stroke, to the potentials at the gap *Q*, which result from the electrostatic induction, and further to note if the quantity in the discharge at *Q* gap is sufficient to puncture the usual kinds of insulations.

Results of the tests with the form of circuit shown in Fig. 7 are given in the table below. In general, it may be stated that the electrostatic induction through 30 ft. (9.14 m.) of wire is sufficient to give potentials of 20,000 to 40,000 volts, under the conditions described. Two choke coils were used, one of five turns of No. 6 B. & S. wire on a 4-in. (10 cm.) wooden core, and the other of twelve turns of the same dimensions. When the 12-turn choke coil was used, higher potentials were induced through the insulation between the parallel wires. When the value of the *G* gap was 3 in. (7.6 cm.) the electrostatic induction produced a spark of 1.2 in. (3 cm.) across the *Q* gap. The spark across the *Q* gap, which represents the insulation of the apparatus on the car, had sufficient brightness and strength to damage insulation.

TABLE OF POTENTIALS OF ELECTROSTATIC INDUCTION BETWEEN PARALLEL WIRES 30 FT. (9.14 M.) LONG

G gap inches	*Q* gap inches	Spark	Needles	Choke coil
1	0.416	snappy	small	5 turns No. 6 wire on 4 in. core
1½	0.532	"	"	"
2	0.625	heavy	"	"
3	0.92	"	"	"
3¼	1.19	"	"	"
3½	1.32	"	large	12 turns No. 6 wire on 4 in. core.
3¾	1.25	"	"	"
5	1.3	"	"	"
3	1.22	"	"	"
2	1.13	"	"	"
1½	1.05	less bright	"	"
1	0.84	"	"	"

UNUSUAL EXPERIENCE OF AN ELECTRIC RAILWAY SYSTEM DUE TO LIGHTNING STORMS

The middle and western portions of Colorado and neighboring States have always furnished an interesting field for lightning arrester installation because of the unusually severe disturbances which arise on all electric systems in these localities, due to lightning storms. The street railway systems have been unable to escape this condition, and the problem of preserving the continuity of service during thunderstorms in these localities has been a very difficult one.

The case of the Denver City Tramway, which operates the majority of the street cars in Denver, and also several interurban lines, is of exceptional interest because of the attention they have paid to the subject of protection and the results they have obtained along these lines. The storm conditions in Denver and vicinity are as severe, in respect to protection, as any that have come to the attention of the writers. Being situated about twenty miles east of the foot-hills of the Continental Divide, storm clouds which form over the mountains invariably pass over the city of Denver or its suburbs, and in this manner as many as two or three storms have been known to occur in one day. The duration of the storms varies anywhere from a few minutes to several hours, but frequently a storm of short duration produces as much damage, independent of its duration, as a much longer storm.

The Denver City Tramway operates over about 100 miles (160 km.) of streets within the city limits and about 50 miles (80 km.) of suburban lines. The rolling stock equipment at present consists of about 300 cars, including work cars, etc. The majority of the cars are operated from one end only.

In years previous to the summer of 1909 this company waged an unceasing battle against lightning. They tried every commercial form of lightning arrester, and a number of experimental devices of their own manufacture, but in spite of all these endeavors to minimize the number of armature failures from lightning, they were forced, during the most severe storms, to suspend entirely the operation of the system. The circuit breakers at the power house and substations were always opened during severe parts of the storms. This interruption of power was a signal to all the car crews to pull down their trolley poles to prevent damage to motors from lightning. In this manner, the system has been known to be at a standstill at times for over an hour, which meant not only a large loss of revenue but a great inconvenience to the public at the time when the weather made it most important to have local transportation.

The suspension of service during the severest portions of storms seemed the wisest course, under the then existing circumstances, not only for the company but also for the public. The large number of cars that would have been disabled by operation during such times would have meant a severely crippled service for some time subsequent to, as well as during the storm. Also the problem of getting disabled cars to the repair barns is always aggravating, even with few armature failures. If many cars were permitted to be damaged the service would be practically as effectively tied up, until the damaged cars were removed, as if the power had been turned off.

As already stated, every known type of lightning arrester, either commercial or experimental, has been tried out to determine its merits, each car being equipped with sometimes as many as two arresters. One of the latest forms of arresters used is what is known as the water box arrester. This was installed on nearly all the cars and in the power house and substations. The form of this device used on cars consisted of a wooden tank about three feet deep, and a foot (30 cm.) diameter, which was filled about two-thirds full of water. A metal plate in the bottom of this tank was connected to the metallic car frame, and the top of the tank was provided with a carbon electrode which was connected to the cable passing from the trolley base to the circuit breaker. The motorman was instructed to pull down the trolley pole and to lower this carbon electrode so that it was in good contact with the water at the approach of a lightning storm, and then to resume the operation of the car until the storm was over, or the power was discontinued at the power house. Besides failing to give adequate protection this arrester was a considerable inconvenience, due to the fact that after about one-half hour's operation it would begin to boil over.

Careful attention had been paid to the matter of line protection, and on some of the more exposed lines, arresters were installed at every trolley feeder tap. These taps are approximately 500 ft. (152 m.) apart.

Shortly after the first installations were made of the d-c. aluminum lightning arrester, this operating company obtained quite a number for installation in its power house and substations and also for installation on a number of the cars. The results obtained with these arresters during the summer of 1909 were so promising as to lead to the equipping of the entire system with d-c. aluminum lightning arresters. Early in the summer of 1910, the work of installing the arresters on the cars was started. The type of arrester installed was the standard 600-volt d-c. aluminum cell lightning arrester. This arrester has no series gap nor any series resistance, thus it is connected directly between the trolley and ground through a 25-ampere fuse. Balancing resistances are used in parallel with the two cells to prevent unequal distribution of potential across them. Fig. 8 illustrates the arrester used, while Fig. 9 shows an arrester installed in the motorman's vestibule.

When the water box lightning arresters were installed they were located in the motorman's vestibule at the No. 1 end of the car. Since this location was the most accessible place in the car the new arresters were installed in the same place. In the case of the old arresters a loop from the trolley pole base had been run down inside the motorman's vestibule through a choke coil, then to the top of the vestibule again, into the circuit breaker. This same loop was used when the new arresters were installed, and is shown in Fig. 10. The ground connection for the arrester was made as short as possible by connecting to the nearest piece of the metallic frame of the car. Another ground connection was run directly to the frame of the motor.

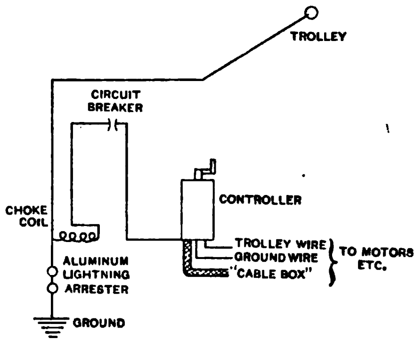


FIG. 10—CONNECTIONS FOR ALUMINUM LIGHTNING ARRESTER AND CHOKE COIL.
As installed on single-end-operated cars of the Denver City Tramway Co.

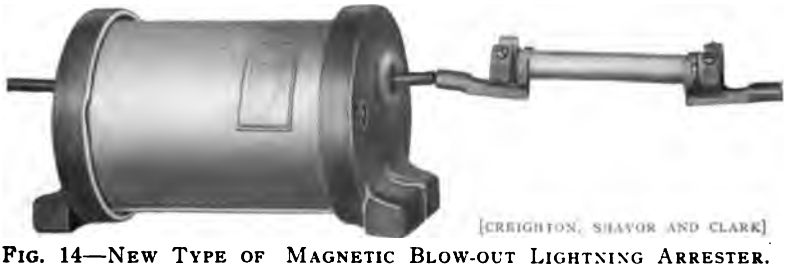
In some of the older types of cars only one circuit breaker was used, or the two circuit breakers were in series and consequently the trolley bus to the controller in the No. 2 end of the car ran through the cable box. To minimize the induction between this trolley wire and also between the ground wire, and other wires in the "cable box," these two wires were removed from the cable box and placed as far from it as the conditions would permit.

[CREIGHTON, SHAVOR AND CLARK]

FIG. 8—1909 MODEL OF 600-VOLT DIRECT-CURRENT ALUMINUM LIGHTNING ARRESTER, SHOWING ARRANGEMENT OF PARTS.

[CREIGHTON, SHAVOR AND CLARK]

FIG. 9—DIRECT-CURRENT ALUMINUM ARRESTER AND CHOKE COIL INSTALLED IN MOTORMAN'S VESTIBULE.



[CREIGHTON, SHAVOR AND CLARK]

FIG. 14—NEW TYPE OF MAGNETIC BLOW-OUT LIGHTNING ARRESTER.

Assembled view, showing series resistance.

The power house and substation lightning arrester equipments were brought up to date by the installation of an aluminum cell arrester on the panel of each outgoing feeder, and in the case of the power house, an aluminum cell arrester was also placed across each generator.

The number of arresters on the trolley line was increased by the addition of all the serviceable gap arresters which were removed from the street cars.

The following table gives a fairly complete summary of the operation of the system during the years of 1909, 1910 and 1911.

COMPARATIVE TABLE

Storms	1909	1910	1911
U. S. Weather Bureau Report[*]....	52	39	31
Cars			
Total number (approximate figure).	279	279x	304
Average No. of cars in operation (approximately)................	170–250	170–250	170–250
Cars re-wired....................	0	193	193
Cars not re-wired................	279	86	more than 86
Cars equipped with direct-current aluminum lightning arrester......	65	278	304
Cars not equipped with direct-current aluminum lightning arrester	214	1	...
Cars reported with armatures damaged by lightning................	102	2	1
Cars protected by aluminum arresters damaged................	8	1	1
Cars protected by aluminum arresters damaged (in per cent.)....	12 per cent.	0.36 per cent.	0.33 per cent.
Otherwise protected cars damaged..	94	1	...
Otherwise protected cars damaged (in per cent.)	43.9 per cent.	100 per cent.	...

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[*] The United States Weather Bureau Report of thunder storms gives only a record of the number of days during the year on which thunder was heard by the station observer. Two storms occurring on the same day would consequently be reported as one, while a single thunder clap would be reported as a thunder storm. Although this report gives a smaller number of thunder storms occurring during 1911 as compared to the two previous years, that season as a whole was unusually severe from the standpoint of lightning disturbances. The storms were, in the opinion of several experienced engineers, as severe as had been encountered during several seasons past.

During the year 1910 new cars were being gradually placed in service and consequently the total number of cars for the year was variable.

According to the above table, during the year 1909 the proportion of cars protected by aluminum arresters which were damaged by lightning was 12 per cent, as compared to the 43.9 per cent of the otherwise protected cars which were disabled from the same cause. During this season, the service was intentionally interrupted a number of times during the most severe portions of several storms.

For the year of 1910 the storm conditions were not considered as severe as during the year following. There were no suspensions of service because of lightning, and only two cars had armature failures from this cause. One of these cars was the only car on the system which was not protected by the aluminum lightning arrester.

During the year just passed, 1911, the storms were very severe, as stated above, but during that time only one car suffered armature failure from lightning. There were no suspensions of service even during the most severe storms. In one instance, on an interurban line, lightning shattered three poles supporting the overhead trolley wire and a car passing at that moment suffered only a damaged arrester.

At the time that the protection of the apparatus of this system was undertaken by the installation of the aluminum lightning arresters, the protection of cars, in light of past experience, seemed so difficult that every known precaution was taken in the installation of these arresters on the cars. Besides making the lightning arrester circuit as short as possible and providing double grounds, the car wiring was rearranged on a majority of the cars. This re-wiring, as has been mentioned previously, consisted in the removal of the trolley bus, when such existed under the car, from the so-called cable box, to a position as far removed from the cable box as possible. The ground wire was treated in a like manner, the trolley bus and the ground wire generally being placed together.

There is no better evidence of the coöperation of Mr. John Evans and Mr. W. H. McAloney, respectively chief engineer and superintendent of rolling stock of the Denver City Tramway, than is shown by their willingness to take this precaution of re-wiring the cars, an entirely new procedure, entailing considerable expense.

The uniformly satisfactory results obtained with all the cars during the years of 1910 and 1911, make it impossible to draw positive conclusions from the records of these two years as to the effects of this re-wiring.

The experience during the year 1909 is noteworthy, however, in that it apparently demonstrates that the re-wiring was a valuable improvement. The foregoing table shows that during that year 12 per cent of the cars protected by aluminum arresters were damaged, whereas, during the two succeeding years, with a majority of the cars re-wired, less than 0.4 per cent of the cars protected by aluminum arresters were damaged, in spite of the fact that they were operated continuously through every storm.

This evidence would be positive enough if it were known that all the aluminum lightning arresters on the cars were in normal condition. There is a possibility, however, that on some of the eight cars protected by aluminum arresters which were damaged in 1909, the arresters had lost a portion of their electrolyte, with a consequent reduction in their protective quality.

The resulting benefits obtained by the installation of the d-c. aluminum arrester may be briefly summarized as follows: Motor failures due to lightning have been decreased to an almost negligible value, and this means a decidedly lower maintenance charge. The reliability of service has been increased many fold during the years of 1910 and 1911, no interruptions chargeable to lightning having occurred during these years.

The cost of installation and maintenance of the arresters in this particular case is more than offset by the decrease in maintenance of motors, and increased revenues, due to continuity of service during thunderstorms, to say nothing of the increased good will of the public who could not understand the justifiable reasons for being discommoded by an interruption of car service.

CHOICE OF THE TYPE OF LIGHTNING ARRESTER

In the foregoing, the demonstrations have been conclusive that the d-c. aluminum arrester gives next to absolutely perfect protection against lightning. The application of the arrester directly connected is to be recommended wherever the lightning is severe and where the service is important. A particular example of railway service where the arrester, directly connected, is advisable, without consideration of other factors, is electric locomotives. The first cost of a locomotive warrants a considerable outlay in any protective device that will give a reasonable insurance against damage to the insulation and thus prevent stalling of a train en route. Putting aside considerations of lightning, heavy-current traction involves greater electromagnetic surges and, consequently, greater risks of flash-overs on the commutators. The aluminum arrester has proved very effective on synchronous converters in preventing flash-overs and should be equally effective on a motor. In generating stations and substations, again, the advisability of using the aluminum arrester, directly connected, can not be questioned. There are conditions, however, where the application of the arrester in its present form is not beyond question. The reasons for this and the location will now be considered.

Where the aluminum arrester is directly connected there is a constant leakage current of about one thousandth of an ampere, consuming about one half a watt, which after a year or two produces an appreciable wear on the aluminum plate. Finally the aluminum film gets in such a bad condition that the electrolyte is boiled out. It is then necessary to obtain more electrolyte and usually to renew the aluminum plates. When the plates become old, more inspection is required to locate the empty jars as soon after they become inoperative as possible, so as not to leave the car without protection. Where lightning troubles are not frequent, operators are loath to give the arresters the desirable inspection and undertake the expense of renewals. There is then a field of application where much depends on the local conditions and the attitude taken by a railway company. This may be considered a border line where the practise is questionable. Across the border are situations where the best engineering dictates the use of the gap type. The protective devices installed along the trolley line for protection against lightning should surely be (in the light of present information) of the gap type. The reasons for this will become apparent when the functions of the trolley line arrester are taken into consideration. The use of the trolley line arrester is to relieve local strain on the line, and thus lessen the duty of the car arresters. The length of the lightning arrester circuit from the trolley over to the pole, down to the ground and back to the rail, is unavoidably long. Furthermore, the distance of any car from such an arrester is, in general, considerable. Therefore, the presence of the series gap is less objectionable than it is on the car arrester. Also, since the line arresters are without attendants, the use of an arrester requiring specific inspection is an uneconomical condition.

The foregoing statements regarding the line arresters apply specifically for the protection against lightning. When it comes to a matter of protecting against electromagnetic surges and " flashing " around the commutator, the gap type of arrester, in the present stage of development, is not efficient.

Addition of the Vacuum Gap and Charging Gap to the D-C. Aluminum Arrester. Under the previous heading an endeavor was made to analyze the different conditions to be met and the characteristics of the aluminum arrester which limited its application. Devices will now be described which widen the application of a d-c. aluminum arrester. As already stated, it is continuous application of potential to the aluminum cells which causes the wear, and thus shortens their life. A very occasional charge will keep the films on the aluminum plates in good condition. Leaving this charging operation to the daily attention of the inspector is out of the question, under the conditions which exist at the present time in the usual car barn. This calls for some automatic device. A charging gap is used which automatically closes the circuit from time to time when the car is in use.

In order to meet the condition of partially dissolved film, which occurs after an arrester has been left disconnected for several weeks, a limiting resistance is placed in series with the charging gap. The drop of potential across this resistance is negligible when the film is in good condition, but otherwise the resistance absorbs enough of the potential to reform the film slowly enough to prevent overheating of the electrolyte.

The use of the charging gap necessarily involves the use of a series gap in a lightning arrester circuit. An old problem in lightning arrester design reappears. A large gap has an objectionably high spark potential. A small gap brings down the spark potential but the gap is very easily short-circuited by the splashing of molten metal from the crater of the arc across the gap. We have had this problem up for solution in the protection of apparatus operating at 100 volts or less, and have been able to produce an arrester with a gap about a millimeter long with a spark potential range anywhere from 500 volts up. This arrester will be described elsewhere. The spark potential chosen for the gap may be either a little above or a little below the potential of the trolley. If the potential of the gap is a little below the trolley potential then an occasional discharge will take place across the gap when the charge in the arrester leaks out sufficiently to bring the difference of potential between the arrester and the trolley to a value equal to the spark potential of the gap.

The phenomenon taking place here is simple. The aluminum cells take a charge like an ordinary electrostatic condenser, and maintain a proportional potential so long as the charge is there. The charge gradually leaks through the film. An arrester in good condition may require several minutes to lose its charge entirely.

Unfortunately, this device can not be used for keeping the film in good condition, as the gap never allows the arrester a charge of full trolley potential. If the spark potential of the gap is set slightly above trolley potential, there is more safety in the operation of the arrester, and very little difference in the protective value. As already stated, the introduction of this gap in series with an aluminum arrester will decrease its protective value by an amount which is yet unkown. Since the spark potential is only slightly above trolley potential, the objection to the gap lies in the unknown value of the dielectric spark lag. Applications of these devices have been made, and information is being gathered at the present time.

The use of the charging gap for the aluminum arrester broadens its field of application. It will become applicable to many cases where lightning is comparatively rare. The engineering practise as a whole is tending towards better car protection, and less protection on the line. This condition is going to be the chief justification for the extra expense and extra trouble that is involved in the use of the aluminum arrester. The chief object is to keep cars moving. One aluminum arrester well installed can save its cost many times over by the decrease in the number of line arresters required.

MAGNETIC BLOW-OUT TYPE OF ARRESTER

The original magnetic blow-out type of arrester was invented by Prof. Elihu Thomson. The design in present use was put in an efficient form by Mr. E. M. Hewlett and so long as the application was limited to potentials of six hundred volts no improvement was found feasible. The increases in trolley potentials to 1200, 1800, and 2400 volts direct current, however, taxed the arc-extinguishing device of a single arrester beyond its limit, and it was necessary either to place two or more arresters in series or reconsider the elements for a new design. It is the theoretical and experimental treatment of these factors of design that it is desired to give in this subdivision of the paper.

There are certain elements fundamental to the arrester which are intrinsically essential to the new design. These essential elements are: A gap with a magnetic field perpendicular to it; a slight amount of series resistance, especially where a battery is used on the circuit, to limit the dynamic current to a value less than a short circuit when a discharge takes place across the gap; and an arc chute to direct and help extinguish the arc.

In the older designs the magnetic field was produced by means of an electromagnet shunted across part of the series resistance as shown in Fig. 12. When this arrester failed to extinguish the dynamic arc it was usually due to the loss of the magnetic field. The insulation of the coil of the electromagnet had necessarily a limit and when the lightning produced a drop of potential across the coil beyond this limit, the coil was shunted out by a spark. With no magnetic field to cause the arc to rise, it remained in the gap and the current continued to pass through the arrester until the energy loss in the resistance rod in series overheated it and a short-circuit resulted. From the information collected, failures of this nature have been relatively infrequent.

In place of an electromagnet is a permanent magnet in the new design. Long pole pieces are placed on the magnet to give a better directed and concentrated field in the path of the arc. The arc is made to play into the loop formed by the steel of the magnet and thus gives the maximum remagnetizing effect at every discharge. As an experiment an arrester was made to magnetize its magnet from a slight amount of residual magnetism. This was done by the first discharge. There are very important advantages that a permanent magnet has over an electromagnet, aside from the elimination of the relatively weak insulation of the coil. One of these advantages is connected with the choice of gap length, and will be described under that heading.

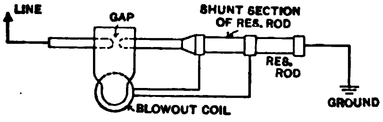

FIG. 12

Gap Length. For the protection of 600-volt apparatus it is naturally desirable to have the spark potential of the gap as little above 600 volts as practicable. In the older form of arrester it was found undesirable to reduce the gap to much less than 25 mils (0.025 in.) (0.635 mm.). This is a little less than 1/32 in. The minimum value of gap setting was determined mostly by the tendency to splash molten metal from the crater of the arc across the gap and thus permanently short-circuit it. The magnetic field around the gap was not strong enough to lift a molten metal bridge out of the gap. There is another factor in the older design that magnified this effect and, furthermore, made it more difficult to pull the arc out of the gap into the arc chute. This factor consisted in the formation of an arc crater on the electrodes before the magnetic field appeared in the gap. The magnetic field coming from an electromagnet is dependent on the establishment of a current in the coil. The time constant of the coil delays for a brief moment the appearance of the magnetic flux. As the summer time goes, this delay is infinitesimal, but in the time required to form a crater it is nearly a lifetime. The formation of a molten crater on the tips of the electrodes has two effects. First, it wears away the points of the electrodes and varies the gap-length; second, it requires more magnetic force to move an arc that terminates in a stable molten crater. When a permanent magnet is used the magnetic field is always present. The arc begins to move as soon as it appears, leaving no time for the formation of a definite crater. With this new condition it is immediately practicable to effect two important changes in the design of the arrester: the mass of metal in the electrodes can be reduced and the electrodes, no longer subject to wear at the gaps, can be fixed once for all with a definite minimum gap setting between them. Furthermore, in the absence of a molten crater, it is permissible to reduce the gap setting. Good results have been obtained with a gap of fifteen mils (1/64 in.) (0.381 mm.)

The Cut of the Electrodes. Although apparently only a minor detail, the angle of cut of the electrodes from the point upward has an important bearing on the successful operation of moving the arc out of the gap. Experiments demonstrated that with the available magnetic force an angle as large as 40 deg. from the vertical at the end of the electrode caused the arc to stick at the point. An angle of less than 10 deg. was too much on the other side, and also produced burning of the electrodes at the points. A full discussion of this feature and the several factors involved is perhaps too detailed to fall within the scope of this paper.

The Arc Chute. The form of arc chute was the subject of exhaustive experiments. At potentials above a thousand volts the form of the arc chute is of prime importance. In the older forms of arrester the arc chute is rectangular, having the dimensions: 25/32 by 1⅛ in. (19.8 by 28.5 mm.) at the top, 7/16 by 21/32 in. (11 by 16.6 mm.) at the bottom, and 2¼ in. (57.2 mm.) high.

The arc is thus constrained to take the form of two parallel streams as it is thrown out by the magnetic field. Even at 600 volts it shoots out beyond the arc chute several inches. At higher potentials, and also at heavier currents than normal, the two arc-streams repeatedly break into each other, which shortens the arc and thus prevents it from attaining a length sufficient to extinguish itself. The natural tendency of the magnetic field is to open the arc into an arch or loop, and the first requirement in a new design is to lengthen the arc chute so the loop can be opened sufficiently to prevent the potential from striking across as the arc is lengthened.

The lengthening of the arc chute is carried down to the lower part at the electrodes. This allows the arc to run back along the electrodes and the craters are formed at spots on the electrodes where burning will do no particular harm.

The next dimension to be determined is the width of the arc chute. Narrowing down the arc chute flattens out the moving arc and by exposing a large surface to the cooling contact with the walls of the chute, chills it and thus aids and hastens its extinguishment. There is, however, a minimum width below which the arc will not be extinguished. This minimum width is reached when the friction of the arc against the walls of the chute becomes so great that the available force from the magnetic field is unable to move the arc rapidly up the chute. Any further restriction causes the arc to hold across the electrodes.

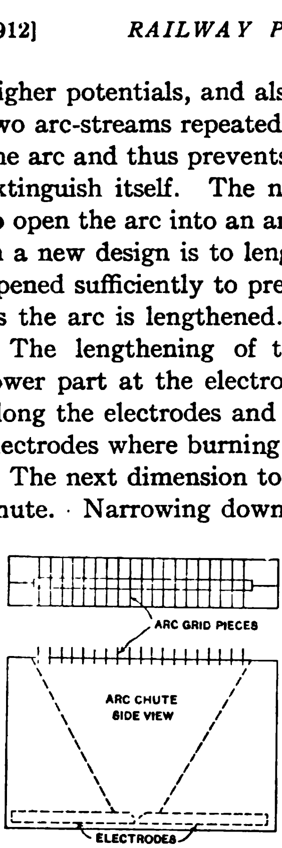

FIG. 13

The Lower Aperture of the Arc Chute. It is necessary to leave an air vent at the lower end of the arc chute to prevent the formation of a partial vacuum back of the moving arc. Without such a vent the air pressure in front of the arc will stop its progress up the chute and the walls of the chute will, consequently, be melted by the intense heat of the arc.

The Arc Grid. If the arc chute is made high enough the arc may be extinguished in the chute. For use with potentials above a thousand volts, the arc chute becomes ungainly in height. Therefore another device is added to aid and complete the extinguishment of the arc. It consists of many metal plates laid on their edges at the top of the arc chute, and perpendicular to the chute. These metal plates are insulated from each other and spaced a fraction of an inch apart. (Fig. 13.) When the arc rises out of the chute it is broken up into as many parts as there are spaces between the plates of the grid. The grid becomes, in effect, a multiple gap arc extinguisher. In these gaps two effects are present. First, the arc is cooled by contact with the cool metal of the grid, and second, each arc absorbs 45 volts or more at its electrodes. Forty-five volts is the minimum potential that can establish an arc, therefore if there are fifteen plates in the grid the arc can not be established between the plates of the grid. Incidentally it may be of interest to note that the effect of this multigap arrangement differs from its usual application to alternating currents. While in direct currents the e.m.f. available for extinguishing the arc is only the potential of the arc, in alternating currents the arc is extinguished naturally at the end of the half cycle and it becomes a matter, not of maintaining an arc, but of reestablishing an arc in the reverse direction in the partially cooled vapors. According to the circumstances, to reestablish the arc requires a potential running up into the hundreds of volts.

By using a grid consisting of sixteen plates or more in an arrester designed for 600 volts direct current, an arc will be entirely extinguished by the grid and will emerge in the form of heated but de-ionized gases. These gases are passed around to the bottom of the arc chute again; thus it is no longer necessary to have the arc discharge into the open. The arrester is, consequently, enclosed and requires no containing box of wood.

Series Resistance. The mechanical conditions call for a resistor of dimensions as small as practicable. The electrical conditions of protection call for as low an ohmic resistance as practicable. Between these two requirements the resistance rod becomes the first part to fail if the current, due to some accidental condition, is not interrupted. This is one reason why the rod is placed outside the metal-porcelain containing box. Another reason for placing the rod outside is for ease of inspection. It is aimed to have the design such that an inspector may be assured that the arrester is in good condition if the resistance rod is intact. Since the arrester is designed especially for line use, it can be inspected in such a position from a trolley car running at full speed. Still another reason for placing the resistance rod externally is to insure, in the few cases of accidental damage, that the circuit can be immediately cleared. One of the most disastrous things to the service is to have a persistently short-circuited line arrester in an enclosed box on a section of a trolley and be compelled to inspect each individual arrester to locate and remove the trouble.

Although the new arrester has an ample factor of safety in the design, it is desirable to allow for extreme and untoward conditions by so constructing it that a persistent short-circuit after the circuit breaker has gone out is impossible. This is accomplished by choosing a resistance rod such that a persistent current through it will overheat and crack it into pieces. On the other hand, the rod will withstand many successive discharges without damage. A single discharge on a 600-volt circuit raises the temperature about 3.5 deg. cent. when the arrester has a 5-ohm series resistance. It is proposed, then, to place the rod out in the open when the arrester is installed on a pole. When installed on a car, however, the rod is to be placed in a porcelain tube in order to insulate it against any possible contact with persons.

Summarizing, a new design has been made of a higher-potential arrester involving a shorter gap length, a permanent magnet that prevents burning at the electrodes, a narrow long arc chute presenting a large cooling surface to the arc, an arc-grid of metal to insure entire extinguishment of the arc, and a return path for the gases. All these parts are entirely enclosed and a resistance rod is placed externally in series. See Fig. 14, Plate XXXVIII.

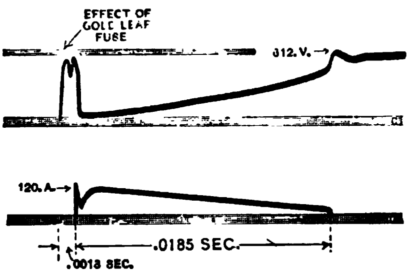

FIG. 15

Oscillographic Studies. Some oscillographic tests are given to illustrate the exact relations of current, potential, and time in the arrester. The first group of oscillograms illustrates the early stages of the development when the effect of the form of the arc chute, strength of magnet, etc., were being determined. The second group of oscillograms was taken on the arrester in its final form.

Oscillogram Fig. 15. This oscillogram is selected to show especially an incidental phenomenon of the test, namely, the effect of poor contact of a strip of gold leaf placed in the gap of the arrester to start the dynamic current. On the potential vibrator, which is the upper record, the potential rises to about 600 volts when the main switch is closed, it then drops slightly, rises again, and then drops back to about 50 volts. Fifty volts is the potential of the arc of 120 amperes as it is first established in a 15-mil (0.038 mm.) gap. It should be noted that the current does not start until the instant of drop of potential to 50 volts. This is more than a milli-second after the potential is applied to the fuse of gold leaf. Although this delay of the establishment of the dynamic current has no practical significance, the length of the delay is remarkable.

As a further comment it required 18.5 milli-sec. to extinguish the arc. During this time the arc was being gradually driven up the arc chute and thereby lengthened; the record of the voltage shows that the potential of the arc rose correspondingly to about 500 volts and then as the arc was suddenly extinguished rose quickly to trolley voltage. Further comments on the details are reserved until the next oscillogram, where they are shown on a larger scale.

Oscillogram Fig. 16. Walls of arc chute of asbestos. Gap leng this 15 mils (0.038 mm.). Resistance in series is 1.7 ohms. Angular cut of electrodes is 15 deg. (Fig. 17). Height of arc chute 3.5 in. (8.89 mm.), length of arc chute 2.5 in. (6.35 mm.). Width of arc chute about ¼ in. (6 mm.) at outer end.

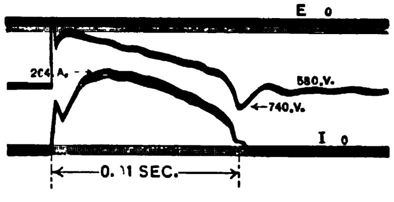

FIG. 16

The upper record is the voltage across the gap alone. The lower record is the dynamic current through the arrester gap. The voltage terminals of the oscillograph happened to be reversed, relative to the current vibrator terminals.

Characteristics of the Current Curve. The form of the current curve is typical of all the tests made in the laboratory on the city trolley circuit. The current rises suddenly, drops back relatively slowly, then rises slowly to a maximum. An exact explanation of this is not known. It seems that the first rush of current comes from the stored energy in the near part of the trolley (the laboratory is about a mile from the power house). Since we would scarcely expect to find so much stored energy in the electrostatic field of a 600-volt circuit, we might look for the stored energy in car motors. After the drop back in the current, the gradual rise on the main part of the wave is evidently due to the choking effect of the inductance in the rails and trolley, and also in the generator. The time constant of this circuit is approximately 1.5 milli-seconds to 2 milli-seconds. The current never reaches its ***maximum possible*** value because as the current rises the arc is being drawn out by the magnetic force and is gradually absorbing the potential. When the current reaches its maximum (in about 3 milli-seconds), the potential across the arc has already risen to over 180 volts.

Characteristics of the Voltage Curve. The spark in this test was started by the discharge of an induction coil. As remarkable a thing took place as in the previously shown oscillogram when the arc was started by means of a gold leaf fuse. The potential across the gap drops suddenly to approximately zero. While the current is rising suddenly to 160 amperes, (about 0.2 milli-seconds,) the arc does not apparently form. At the end of this time, however, the arc suddenly assumes a potential of 230 volts, and gradually drops back to about 100 volts before it again begins to rise. An explanation of this is not evident on the face of it. Apparently the explanation is as follows: At the first instant the spark from the induction coil starts the dynamic current but the spark cannot form into an arc because a strong magnetic field is moving the spark up the cut of the electrodes so rapidly that no spot is given sufficient heat to form a crater. Without a crater no metallic vapor is formed. The characteristic of an arc is the electric conduction by the vapor of the electrodes. A spark, which is heated air, is the conductor in this case. It has dead resistance but no appreciable apparent counter e.m.f. similar to the drop of potential at the

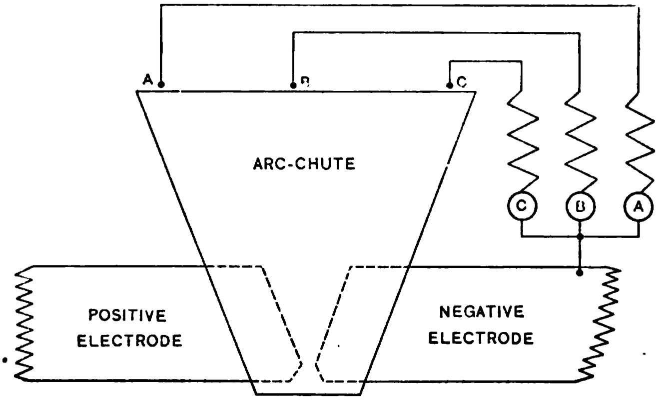

Fig. 17

positive electrode of an arc. As soon as the spark is lifted out of the 15 deg. angle of the electrodes its terminals are carried more slowly horizontally along the electrodes and there is time given to heat the copper at a spot to the melting temperature and consequently the arc appears.

With a current of more than 100 amperes flowing when the arc potential first appears it is not at all evident why the initial arc potential should be as great as 230 volts. An attending circumstance is a decreasing value of current at this time. When an arc is formed by a gradually increasing current the potential starts high, and diminishes as the current increases, but here is a case where the current is high and simultaneously the potential across the arc is also high. The question arises—what has become of the conducting gases of the spark? No matter what scientific explanation is given of this phenomenon, there is one practical result of great value in the operation of the lightning arrester: there is not the slightest indication of burning at the sharp points of the electrodes due to the discharge.

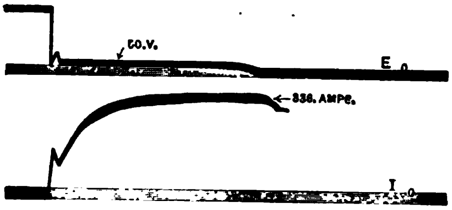

FIG. 18

Commenting on the later part of the voltage curve, the potential rises uniformly in a most desirable manner until the arc current drops to about 80 amperes. At this time the potential across the arc is nearly full trolley potential and the arc becomes unstable and flicks rather suddenly. As the arc is extinguished the surge of electromagnetic energy raises the potential of the trolley to 160 volts above its normal value. While there is no harm in this small rise it is an indication that it is possible to make the design such as to greatly magnify this value. At the time these tests were made it seemed undesirable to reduce the total time of the arc below 4 milli-sec. It is not a question of strain on the insulation by this rise of potential so much as an increased risk of starting a " flash " around the commutator of some motor in the neighborhood. The final design must exclude this objectionable feature.

Incidentally the oscillogram shows that the natural period of oscillation of the trolley system is about 3 milli-sec., or in terms of the frequency, 333 cycles per sec. This is shown by the oscillation in the potential curve after the current is reduced to zero.

Oscillogram Fig. 18. This oscillogram is given to show especially the bad effect of large angular cut of the electrodes. In the previous oscillogram the cut of the electrodes was 15 deg. from the vertical. In the present oscillogram the only change is to a cut of 38 deg. to the vertical. The result was that the arc was not extinguished by the arrester and the circuit breaker in series finally opened the circuit. The electrodes were very badly burned at the points, showing that the arc did not rise.

Comments on the Current Curve. Again the characteristic rise of the current in the d-c. circuit at some distance from the power house appears. In this case the current was not limited and it rose to its full value of 336 amperes. The light of the vibrator was cut off before the circuit was opened, therefore the curve is shown incomplete—that is to say, it does not return to zero.

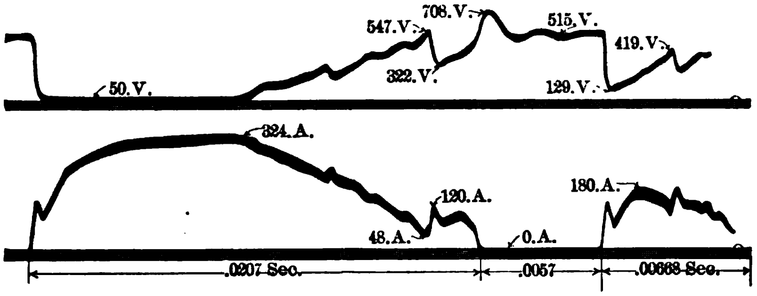

FIG. 19

Comments on the Potential Curve. The beginning of the potential curve differs considerably from the one given in the previous oscillogram. The potential does not drop to zero when the current starts, but maintains its full value for a brief period, then drops to a low value and rises as the current drops back after the first current rush. The potential then drops to approximately 50 volts and retains its value constantly, showing that there was no elongation of the arc.

Oscillogram Fig. 19. This test is a repetition of the previous test. New electrodes were placed in the arrester with the same

38-degree angular cut from the vertical. The objectionable feature of this large angle at the electrode is again represented in this oscillogram, although the arc was finally extinguished after the second trial.

General Comments. The voltage curve at the start is again different from all the preceding oscillograms. In this case the voltage drops rapidly at first and then gradually to 50 volts without any reversal on the way. It will be noted that in this case again the arc sticks in the electrodes and the potential remains about 50 volts for nearly 10 milli-sec. The arc, however, is shifted out of the electrode, although it sticks back along the electrodes several times in rising. Finally after about 21 milli-sec. the arc is put out. After about 6 milli-sec. more of zero current there was evidently a second, and accidental, discharge from the induction coil starting the arc again across the gap. Since the electrodes were already burned back the arc was extinguished the second time much more easily than the first time. The light on the film was cut off the voltage vibrator a little bit early, and, therefore, the record is not complete back to trolley potential. This oscillogram shows a bad condition both for the electrodes and the arc chute. The condition of the arc chute was not brought out in the previous oscillogram.

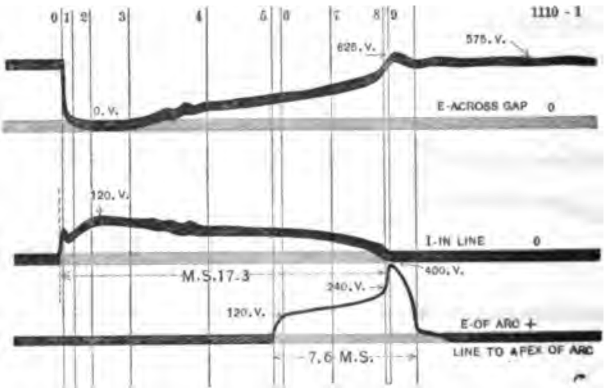

FIG. 20

Oscillogram Fig. 20. A resistance of 6.7 ohms was in series and the angular cut of the electrode was 5 deg. It will be noted that the arc stuck between the electrodes for a considerable time. In this case the trouble was due not to the angular cut of the electrode so much as to the lack of force from the magnetic field of the arc. It will be noted that by an increase in the series resistance the current has been materially reduced and the force on the arc is directly proportional to the value of the current. In this case it required 17.3 milli-sec to extinguish the arc.

In this stage of the development the value of allowing an air vent under the electrodes was not fully appreciated and it may be that this factor is also involved in holding the arc in the gap longer than is desirable.

A third record is shown in this case to determine the time of rise of the arc in the arc chute. A voltage vibrator was connected with one terminal to the negative electrode, and the other terminal was connected to the platinum wire shown at *B*, Fig. 17, which was laid across the outside of the arc chute directly above the electrodes. The distance was 3¼ in. (82 mm.) from the electrodes to the platinum wire. It required 11½ milli-sec. for the arc to reach this platinum electrode. It will be noted also that after the series current in the arrester ceases there still remains an arc from the positive electrode to the platinum wire. These hot gases remain conductive to the 0.1 ampere taken by the voltage vibrator for 1.3 milli-sec. after the main arc has been interrupted.

Cross lines are drawn on oscillogram Fig. 20 to relate the records to equal time. The following list is given of the time relations:

From line 0 to line 1 the voltage drops to the arc value or practically zero in 0.6 milli-sec. The voltage remains at this low value for 3.1 milli-sec. At cross line 2 the current rises to 120 amperes. In the time between the cross lines 3 and 5 the current gradually drops and the voltage rises. Cross line 5 is timed when the arc strikes the platinum electrode, and is 11.5 milli-sec. from the beginning. Between cross lines 5 and 6, which is 0.4 milli-sec., the arc potential at the platinum rises to 120 volts above the negative electrode. In other words, this is the drop of potential from the middle of the arc to the negative electrode. At the cross line 8 the main current is reduced to zero and the voltage from the platinum electrode to the negative terminal constantly rises from 240 volts to 400 volts. The rest of the 575 volts of the trolley, that is, 175 volts, is the drop in potential along the arc from the platinum wire to the positive terminal. The time between cross lines 8 and 9 is 0.2 milli-sec. After the main current ceases, the arc vapor between the positive electrode and the platinum exploring wire gradually cools, as the tenth of an ampere taken by the oscillograph is not sufficient to maintain the vapor conductive. This arc gradually absorbs the voltage away from the oscillographic voltmeter and reduces the voltage to zero. This requires 1.3 milli-sec.

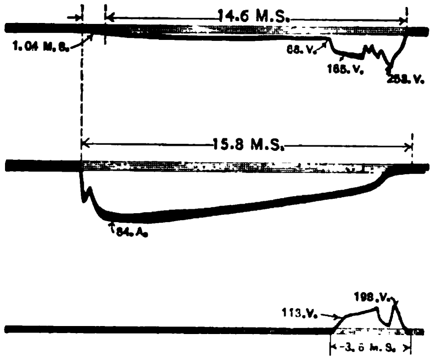

FIG. 21

Oscillogram Fig. 21. A series of tests was subsequently made to determine the position of the arc relative to the electrodes and arc chute, at every instant. It is thought that the details of this study are too much involved to be of general interest,

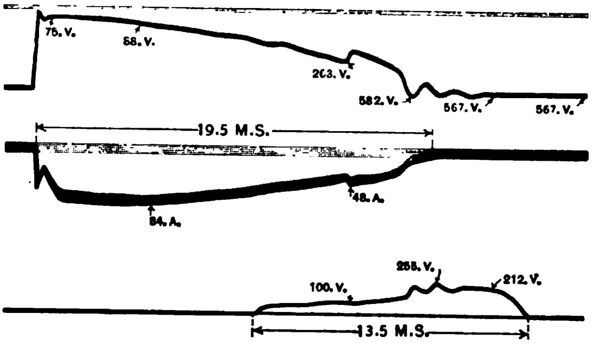

FIG. 22

and therefore these oscillograms are omitted. Oscillogram Fig. 21, however, is given to show two positions of the arc. This illustrates the method of study.

The platinum exploring electrodes were located at the points *A* and *B*, as shown in Fig. 17. *A* is at one end of the arc chute, over the positive electrode, and the point *C* is at the other end of the arc chute, over the negative electrode. In both records 1 and 3 on the oscillogram the other vibrator terminals are connected to the negative electrode. These exploring voltage vibrators then measured the drop of potential from *A* to the negative electrode along the arc, and from *B* to the negative electrode along the arc, so long as the arc was complete between the positive and negative electrodes.

Oscillogram Fig. 22. Subsequent to the last oscillogram, carbon electrodes were laid on top of the copper electrodes in such a way that after the arc was raised out of the gap the craters formed on the carbon. This carbon arc was more difficult to extinguish than the copper arc. With all conditions the same, the time was increased from 15.8 to 19.5 milli-sec.

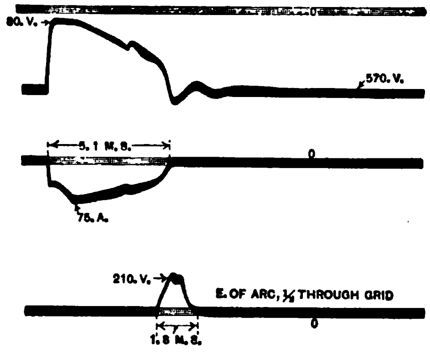

FIG. 23

Oscillogram Fig. 23. In this oscillogram a metallic grid was used over the arc chute to aid in extinguishing the arc. In order to determine how far through the grid the arc penetrated, the platinum electrode at position *B*, Fig. 17, was inserted half-way through the grid. The arc reached this electrode, as shown in the lower record. The resistance in series was 6.6 ohms. The arc was extinguished in approximately 5 milli-sec. One small irregularity in the decrease of the current is shown, but the arc was extinguished without any heavy surge in potential.

The grid consisted of 17 pieces of flat copper sheet spaced ⅛ in. (3.2 mm.) apart. The depth of the grid was ⅞ in. (22.2 mm.) In the lower record the other terminal of the voltage vibrator was connected to the positive electrode. The fact that the current persisted in this vibrator after the main current had been reduced to zero shows the persistence of the vapor at positive electrode even after it is cooled at the negative electrode.

Oscillogram Fig. 24. This oscillogram was taken with slight improvements in the arc grid and the arc chute. The resistance in series was the same as in the previous case. Decrease in current and change of potential are satisfactorily uniform. The exploring electrode of platinum was placed just below the top of the arc grid. The absence of any curve on the lower vibrator indicates that the arc did not reach the exploring electrode.

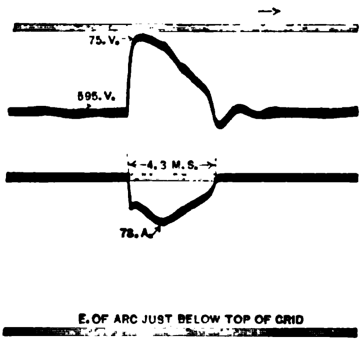

Fig. 24

Oscillogram Fig. 25. In contrast to the oscillogram Fig. 24 where the operation of the arrester was satisfactory, this earlier oscillogram is given to show an improper design of arc chute and auxiliary devices. In this oscillogram the arc chute was shortened and a metallic ladder placed up the side of it. The arc chute was so short that as the arc rose into an arch it kept restriking across a shorter length for a considerable time. This is a condition that never exists in a normal arc chute of porcelain, and shows the impracticability of using a metallic ladder in the arc chute under the conditions tried. The duration of current was 35 milli-sec.

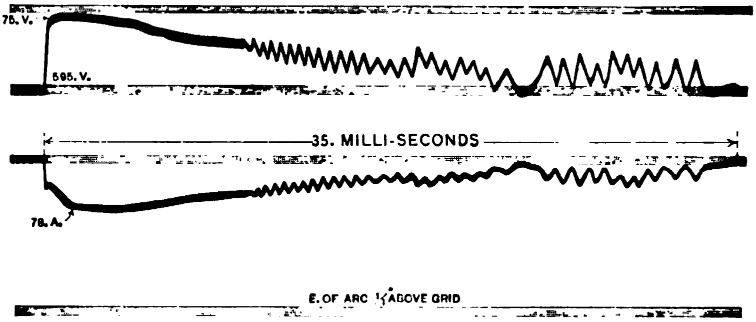

Fig. 25

Oscillogram Fig. 26. Discharge of a lightning arrester on 1790 volts direct-current—lightning arrester placed near the generators. Potential furnished by two generators in series, rated 500 kw., 1500 volts, each machine under-excited. Resistance in series, 20 ohms. Maximum current, 60 amperes; total time of discharge, 16 milli-sec.

The voltage wave shows a drop from 1790 volts to 210 volts at the first instant of discharge. This large drop is accounted for by the large reactance in the generators. This same reactance of the generator causes a rise in potential over the normal potential of the circuit when the arc has been extinguished in the arrester.

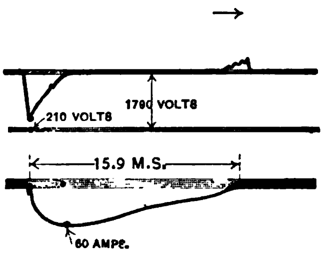

FIG. 26

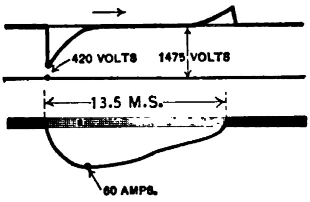

FIG. 27

Oscillogram Fig. 27. Discharge of lightning arrester on 1475 volts, direct current. Lightning arrester placed near the generator. Potential furnished by two generators in series, rated at 500 kw., 1500 volts, each machine under-excited. Resistance in series, 15 ohms. Maximum current, 60 amperes; total time of discharge, 13½ milli-sec.

Again in the voltage wave is shown the rise of potential at the end of the discharge due to the inductance of the generator.

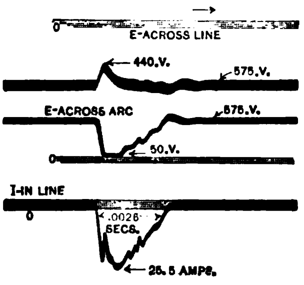

FIG. 28

Oscillogram Fig. 28. Discharge of single arrester on 575 volts, at one mile (1.6 km.) from the source of power. Potential furnished from the city trolley. Resistance in series, 22 ohms.

In this record not only the current in the arrester and the potential across the line are given, but also the potential across the arc in the arrester. By arrangement of the oscillograph, the potential vibrators deflected in the opposite directions

The potential across the arc drops to 50 volts at the first instant of discharge, and the potential across the line drops to 440 volts. Both potentials recover their original values in a somewhat irregular manner.

The irregularity in the potential is due to the variations in the current, which in turn are due to the condition of the arc chute. The total duration of the arc is 2.6 milli-sec.

It will be noticed in the middle record that the voltage across the arc sticks at 50 volts for a considerable fraction of the whole duration of the arc. This is due to the fact that the current is reduced to a value so low that the force from the magnet is not sufficient to drag the arc out of the gap quickly. In each of the following oscillogram figures, the resistance is successively lowered.

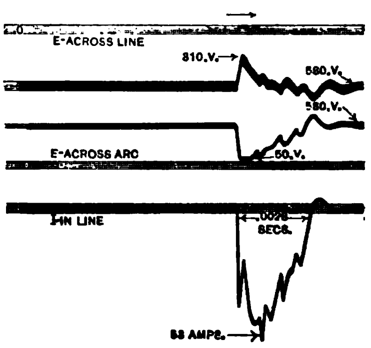

FIG. 29

Oscillogram Fig. 29. Discharge of single arrester on 580 volts at one mile (1.6 km.) from the source of power. Potential furnished from the city trolley. Resistance in series, 10 ohms.

In this record not only the current in the arrester and the potential across the line arc given, but also the potential across the arc in the arrester. By arrangement of the oscillograph the potential vibrators deflected in opposite directions. The potential across the arc drops to 50 volts at the first instant of the discharge, and the potential across the line drops to 220 volts. Both potentials recover their original values in a somewhat irregular manner.

The irregularity in the potential is due to the variations in the current, which in turn are due to the condition of the arc chute. The total duration of the arc is 2.5 milli-sec. The slight reversal of the current as it is extinguished is due to the presence of an aluminum cell which was used to protect other apparatus on the same line.

Oscillogram Fig. 30. The conditions of this oscillogram are similar in every way to those of the previous oscillogram except that the resistance was reduced to five ohms. Variations in the current potential are somewhat more marked.

Oscillogram Fig. 31. The conditions for this oscillogram are the same as for the previous one, except that no series resistance was used. In this case the arrester was depended upon to draw out the arc more rapidly than the current rose in the circuit in order to limit the value of current in the arrester to less than short-circuit value.

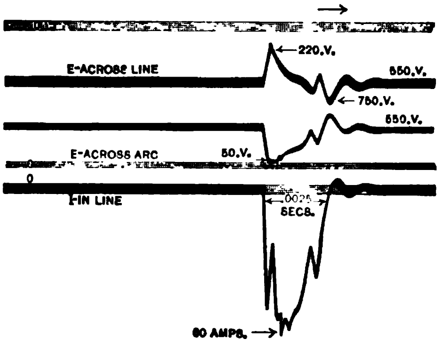

FIG. 30

The current and potential waves are very much smoothed out, due to a better condition of the arc chute. The current rose to a maximum of 184 amperes with a duration of 4.3 milli-sec. It has been pointed out before that the initial rise and drop in the current which is characteristic of the discharge at some distance from the power house is probably due to the capacity effect of the line.

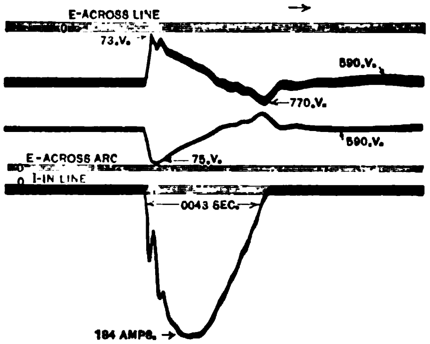

FIG. 31

In the foregoing selected tests the endeavor has been to show how the elements of design of a lightning arrester are predetermined, and the methods used for doing it. No attempt has been made to show the tests and methods for determining all the detailed relations of the different parts and dimensions of arc chute, dimensions and spacing of arc grid, strength of magnetic field, distribution of magnetic field, total energy dissipated in the series resistance, total permissible energy in the resistance, quantity of electricity, time of discharge, etc., but it is hoped that sufficient experiments have been shown to demonstrate that the design of the lightning arrester can be made with as great an accuracy as any other commercial electrical apparatus. It is possible to state what an arrester will do under various conditions of discharge imposed upon it, and what degree of protection it will give under each condition. In other words, it is possible to state the limitations of each arrester, when it will fail to protect, and when it will fail to extinguish the dynamic arc and be self-destroyed. Each arrester requires a specific rise of potential before it will spark, and after the spark it will allow a definite value of current to flow without raising the potential to a dangerous value. This value of current is determined by Ohm's law. For example: If an arrester has 20 ohms in series, then at 1200 volts, which is double the usual trolley potential, the discharge current will be 60 amperes. If the gap sparks over at 1200 volts and the lightning discharge is relieved by a discharge of 60 amperes, then no damage should result. If, on the other hand, the resistance in the lightning arrester is 2400 ohms, then in spite of the fact that the gap sparks over on 1200 volts the arrester cannot discharge at a greater rate than ½ ampere, and it is, therefore, limited to discharges which will be relieved by a discharge rate of ½ ampere.

It will be seen from this discussion that an arrester can be designed to discharge safely lightning strokes of any desired intensity, and that it is entirely a question of compromise between the cost of the arrester, on one side, and the percentage of lightning discharges that the arrester will take care of, on the other side. Under the best conditions attainable in this type of arrester it cannot be made to give as perfect protection as the aluminum cell arrester. On the other hand, its up-keep is less, at the present time.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

PROPAGATION OF IMPULSES OVER A TRANSMISSION LINE

BY J. H. CUNNINGHAM AND C. M. DAVIS

The investigations outlined here were made last summer on the artificial transmission line described in a previous paper.[1] Briefly, this line consists of 400 glass cylinders 6 in. (15 cm.) in diameter and 4½ ft. (136 cm.) long. Upon these are wound 240 turns of No. 8 B. & S. copper wire and the inner surface is lined with tinfoil, cut so as to avoid secondary currents. The constants of the total line are as follows:

Capacity	1.153×10^{-6} farad.
Inductance	0.411 henry
Resistance	96.2 ohms

Natural period $= \dfrac{1}{4\sqrt{L\,C}}$ 363 cycles (quarter wave)

Equivalent length $= \dfrac{186{,}000}{4\,f}$ 128 miles = 206 km.

The line is equivalent to one wire 128 miles long with resistanceless ground return, that is, one phase of a grounded Y system.

Voltage impulses were sent over this line and were produced by suddenly impressing a continuous voltage upon the low-tension winding of the step-up transformer to which the line was connected. This caused the current, and with it the flux, to rise, and in turn induced a voltage in the high-tension winding and the line.

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[1] *Design, Construction and Test of an Artificial Transmission Line,* TRANSACTIONS A. I. E. E., 1911, XXX, I, p. 245.

Difficulty was experienced in finding a suitable switch with which to close the circuit. After trying an ordinary knife blade switch, a solenoid-operated carbon contact switch and an oil switch, a very simple drop switch proved to give the best results. This consisted of a copper rod dropping about seven inches into a cup of mercury. The contact was always positive and gave currents and voltages free from all irregularities due to arcs or multiple contacts.

The transformer used was rated at 125 cycles, 3 kw., 110/2200 volts, and was modified in construction by removing one end of the core in order to increase the magnetic energy, $\frac{Li^2}{2}$, so as to get an impulse of sufficient energy to be observed by the oscillograph. This open magnetic circuit also eliminated the effects of saturation.

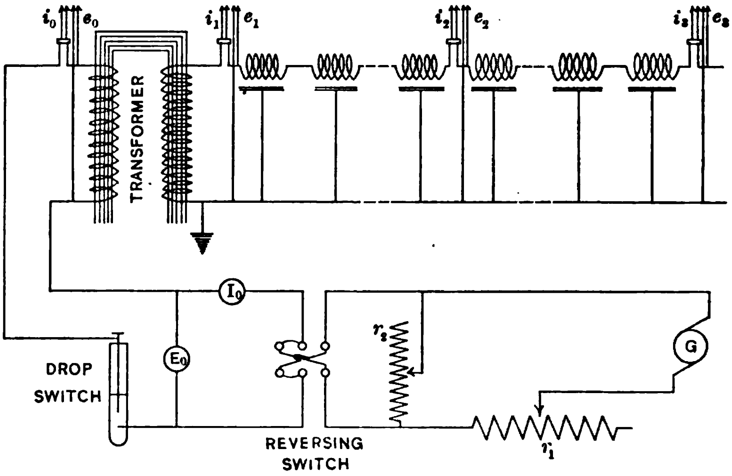

Fig. 1

The method of operation can be described by reference to Fig. 1. The transformer was connected to the generator with the resistance r_1 in series and the resistance r_2 in parallel. The reversing switch, drop switch and oscillograph vibrators were connected as shown. The object of the arrangement of resistances r_1 and r_2 was to control the magnitude and character of the impulse by controlling the current and voltage.[2] With the

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[2] See *Disruptive Strength with Transient Voltages*, by J. L. R. Hayden and C. P. Steinmetz, Transactions A. I. E. E., 1910, Vol. XXIX. Part II, page 1125.

drop switch closed the resistance r_1 was adjusted to give the desired current, I_0, and with it open the resistance r_2 was adjusted to give the desired voltage E_0. Tests were made with $I_0=$ 25 amperes and $E_0=75$ volts, and with $I_0=25$ amperes and $E_0=225$ volts.

The reversing switch was inserted so that by throwing it over and back each time before taking a record the residual magnetism was constant in direction and amount.

With I_0 and E_0 adjusted, the drop switch was closed and oscillographic records of the voltage and current were made on the low-tension side of the transformer, at the beginning, at the middle and at the end of the line. Time was marked by a 60-cycle voltage wave. Records were made thus with the transmission line open at the end, short-circuited at the end and closed by 600 ohms $\left(=\sqrt{\frac{L}{C}}\right)$ non-inductive resistance.

Several of the oscillograms taken are reproduced herewith, and a study of them is interesting. Fig. 2 shows the current and voltage on the low-tension side of the transformer when the line is not connected to it. Fig. 3 shows the same impulse on both the low-tension and high-tension sides of the transformer: e_0 and e_1 respectively. The curve e_1, then, gives the general shape of the voltage impulse impressed upon the line. A 60-cycle timing wave is also shown, from which it is observed that the impulse lasts about one cycle, or 0.017 second.

If the line were infinite in length the impulse would travel out over it until all its energy was dissipated and it would thus vanish. This condition can be reproduced on a line of finite length by closing the end with just enough non-inductive resistance to absorb all the energy of the impulse. This resistance is numerically equal to $\sqrt{\frac{L}{C}}$. Figs. 4 and 5 show the voltage and current of an impulse propagated over such a line. The curves e_1 of Fig. 4 and i_1 of Fig. 5 show the voltage and current at the beginning of the line, e_2 and i_2 at the middle, and e_3 and i_3 at the end of the line.

The figures just referred to show very clearly how the impulse progresses along the line, dying out in intensity as it goes. The velocity of propagation can also be observed by noting the points at which the successive curves begin. Thus e_2 begins a little later than e_1, similarly e_3 begins a certain time after e_2 and twice this time after e_1. The same may be observed in the case of i_1, i_2 and i_3. The velocity of propagation was measured as 0.78 milli-second; that is, 0.78 milli-second after the drop switch was closed the impulse reached the end of the line. Since the velocity of propagation over a straight transmission line in air is known to be that of light, 3×10^{10} cm. per sec. (neglecting resistance), the artificial line has an equivalent length of 233 km. (145 miles), or about 13 per cent longer than calculated from the measured inductance and capacity.

If the line is not infinite in length, and, furthermore, if it is short enough so that the impulse does not die out before reaching the end, it is interesting to see what takes place. The impulses which are impressed upon the line are impulses of *energy*, although the oscillograms we obtained of them show only the component parts, the voltage and the current. On a line of infinite length the impulse of energy would travel along until it was all dissipated, but on a short line it reaches the end, and, depending upon the electrical condition at the end, it is disposed of in various ways. We will consider two cases in detail; first when the line is open, and second, when it is short-circuited.

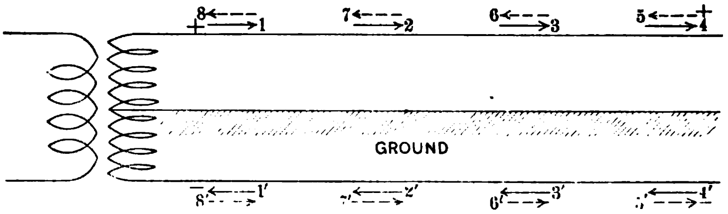
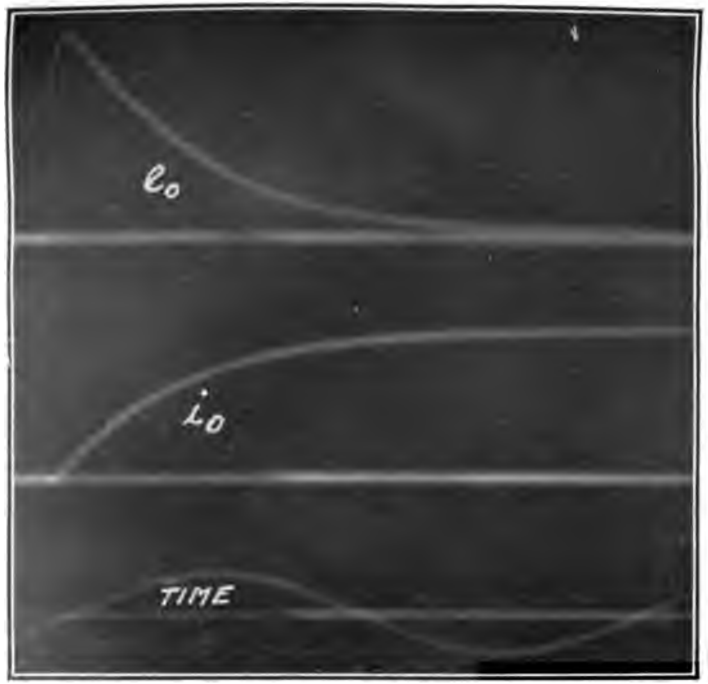


FIG. 6

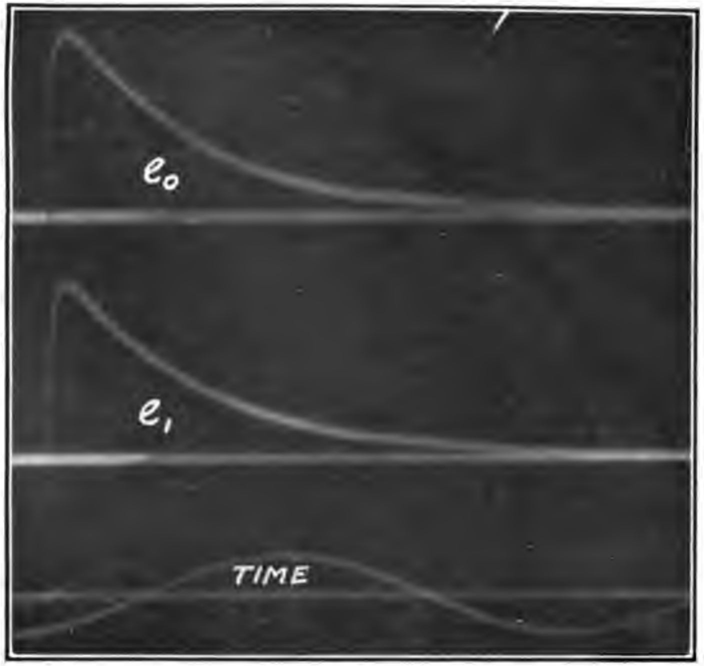
Taking the case of the open line and referring to the diagram, Fig. 6, the transmission line is represented connected to a transformer, the middle of which is grounded.

Assume that the impulse is of such polarity that when it is impressed upon the line it makes the upper line positive, as indicated. The voltage of the impressed impulse causes corresponding currents to flow, as shown by the arrows 1 and 1′, which flow in the direction corresponding to the direction of the voltage. These two currents with their voltages now travel along the line and at some later instant are at positions 2 and 2′. (The numerals are placed at the ends of the arrows in the direction of propagation along the line.) At a later instant they are at 3 and 3′, and finally reach the end of the line, 4 and 4′. Now



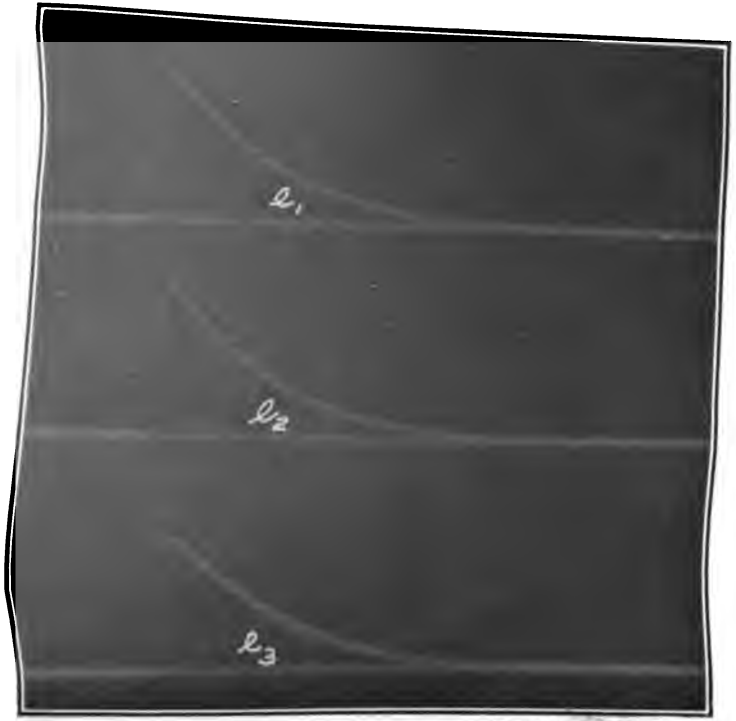
[CUNNINGHAM AND DAVIS]

FIG. 2—LOW-TENSION VOLTAGE AND CURRENT
No line on.



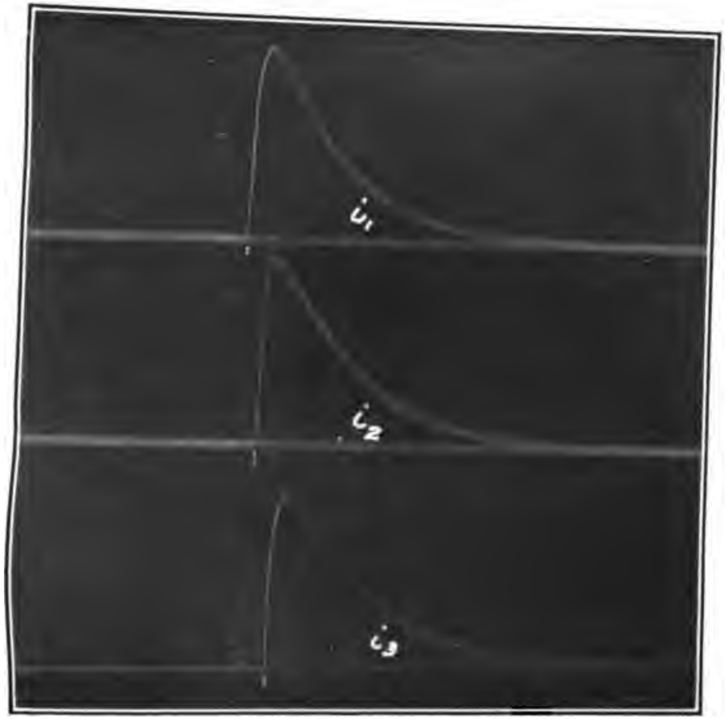
[CUNNINGHAM AND DAVIS]

FIG. 3—LOW-TENSION VOLTAGE AND HIGH-TENSION VOLTAGE.
No line on.



[CUNNINGHAM AND DAVIS]

FIG. 4—VOLTAGES AT THE BEGINNING, MIDDLE AND END OF LINE.
Line closed through 600 ohms.



[CUNNINGHAM AND DAVIS]

FIG. 5—CURRENTS CORRESPONDING TO FIG. 4

the energy is at the end of the line, but it will not stay there if there is a possible outlet for it. Obviously, since the line is open, the only outlet is back the way it has just come; thus, the current reverses and the energy travels back to the home end of the line as indicated by the dotted arrows. Since at the moment of the reversal the far end of the line becomes the source of energy and the current takes the direction as shown by the dotted arrows, the voltage must have a direction as indicated by the plus and minus signs at the far end.

The case of the short-circuited line is represented by the diagram Fig. 7, where, as before, the impulse is represented as starting with the currents 1 and 1′, and the voltage as indicated. Similarly, this impulse travels along the line until it reaches the far end, but now there is an outlet for the energy afforded by the short circuit, so the currents in the two wires merely keep on flowing around the circuit and the energy flows back as indicated by the numerals. In this case, at the moment of reversal, when the far end becomes the source of energy, the direction of the voltage would have to be as indicated by the plus and minus signs.

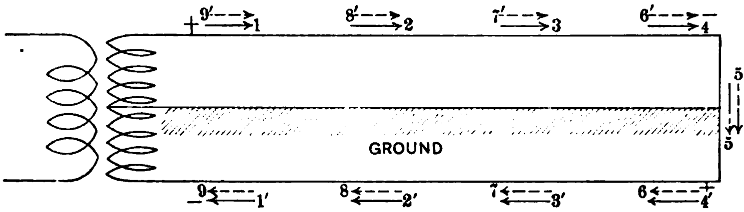


FIG. 7

As far as the energy is concerned the two cases just described are identical; in both, the energy travels from the home end to the far end of the line and back to the home end again, and if it is not all dissipated by the time it gets back to the starting point, it will again travel out over the line, continuing thus back and forth until it dies out. We may therefore consider the energy impulse as being " reflected " each time it reaches the ends of the line. Likewise, by analogy, we may speak of the current and voltage of the energy impulse as being " reflected, " and since in this investigation we know of the energy only through the agency of oscillograms of current and voltage, it is a very useful term.

By the above study of reflection from open and short-circuited lines we see, in the case of the open line, that the voltage remains in the same direction and the current reverses after reflection, while in the short-circuited line the opposite is true—the current remains in the same direction and the voltage reverses.

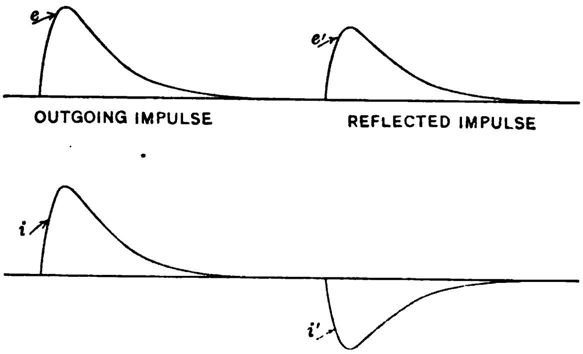


Fig. 8

There are other conditions which may exist at the far end of the line, viz., closed by inductance, by resistance, or by any combination of them. When the line is closed by an inductance part of the current passes over it, as with a short circuit, and part returns by the same wire it started over. Thus the reflection is intermediate in nature between the reflection from open circuit and that from short circuit.

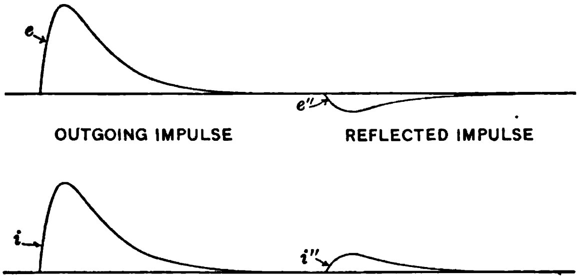


Fig. 9

Figs. 6 and 7 show the line as composed of two line wires with the ground midway between them electrically. On the artificial line the connections were such as to give only one wire with a ground return. This would be the case in a three-phase Y-connected system with grounded neutral and two of the line wires disconnected.

In order to get a clear idea of the way these impulses and their various reflections may be recorded by an oscillograph, let the line be assumed so long that the out-going impulse has time to die away before the reflected impulse returns to the home end of the line. If an oscillogram of the voltage and current were taken at this end it might look something like Fig. 8, which shows the outgoing impulse, e, i, and the same impulse reflected from the open end of the line, e', i'. Similarly, another oscillogram may be assumed giving the reflection from an inductance. This is shown in Fig. 9. Here the inductance is taken of such a value that it acts nearly as a short circuit, that is, the voltage reverses.

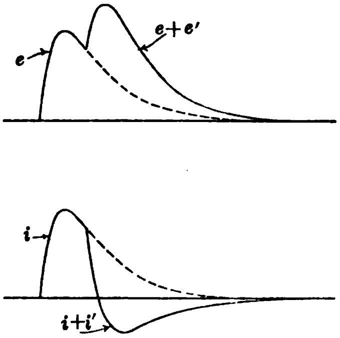


FIG. 10

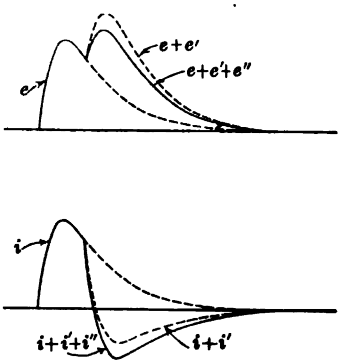


FIG. 11

Should the line be short in comparison with the length of the impulse the reflected wave will return before the outgoing impulse has died out, and an oscillogram would appear as shown in Fig. 10, where the reflected impulse is combined with the original impulse. Further, when the oscillogram is taken at the beginning of the line it will show not only the reflection from the far end but simultaneously with it the second reflection from the transformer coil at the beginning of the line. The latter is of the nature of that shown in Fig. 9. Finally, then, an oscillogram taken at the beginning of the line would appear as in Fig. 11. An actual oscillogram is shown in Fig. 12 which gives e_1, i_1 and a 60-cycle timing wave, when the line is open at the far end.

When the line is short-circuited at the end, corresponding reflections exist, but with the voltage, instead of the current, reversed after the first reflection. Fig. 13 is an oscillogram taken at the beginning of the line; Fig. 14 shows the progression of the current along the line.

In the oscillograms just referred to it will be noticed that there is more than one reflection, in many cases three are easily seen. This means that the impulse does not die out until it has traversed the length of the line more than six times. The reflections after the first one may be analyzed in the same manner as outlined above.

It is interesting to investigate the agreement between the observed impulses and those calculated from the line and circuit constants. Obviously, from the observed impulses the line constants may be calculated, and by comparing these with the line constants determined by observation with 60-cycle steady voltage, the change of the line constants due to the transient nature of the impulse studied.

For this purpose, the oscillograms are first reduced to empirical equations by the usual method,[3] and the theoretical meaning of these equations is then studied. At present this work is not yet sufficiently completed for presentation, and it will be given at some other time.

It was found that the oscillograms are best represented by exponential expressions.

For instance, with 75 volts impressed upon the transformer primary, and a transformer ratio of 10 to 1, the expressions of voltage and current were found to be:

1. No line on and transformer open-circuited at the secondary:
   Primary impressed voltage $e_0 = 63\ (\epsilon^{270t} - \epsilon^{6500t})$
   Primary current $i_0 = 25\ (1 - \epsilon^{290t})$
   Secondary terminal voltage $e_1 = 670\ (\epsilon^{280t} - \epsilon^{12800t})$

2. Line connected to the secondary terminals of the transformer, and closed through a non-inductive resistance of about 600 ohms (equal to the surge impedance):

a. At the transformer end of the line
   Voltage $e_1 = 440\ (\epsilon^{-200t} - \epsilon^{-5800t})$
   Current $i_1 = 0.85\ (\epsilon^{-200t} - \epsilon^{-5800t})$
b. In the middle of the line
   Voltage $e_2 = 430\ (\epsilon^{210t} - \epsilon^{3300t})$
   Current $i_2 = 0.84\ (\epsilon^{210t} - \epsilon^{-3300t})$
c. At the receiving end of the line
   Voltage $e_3 = 400\ (\epsilon^{-198t} - \epsilon^{-3600t})$
   Current $i_3 = 0.68\ (\epsilon^{198t} - \epsilon^{3600t})$

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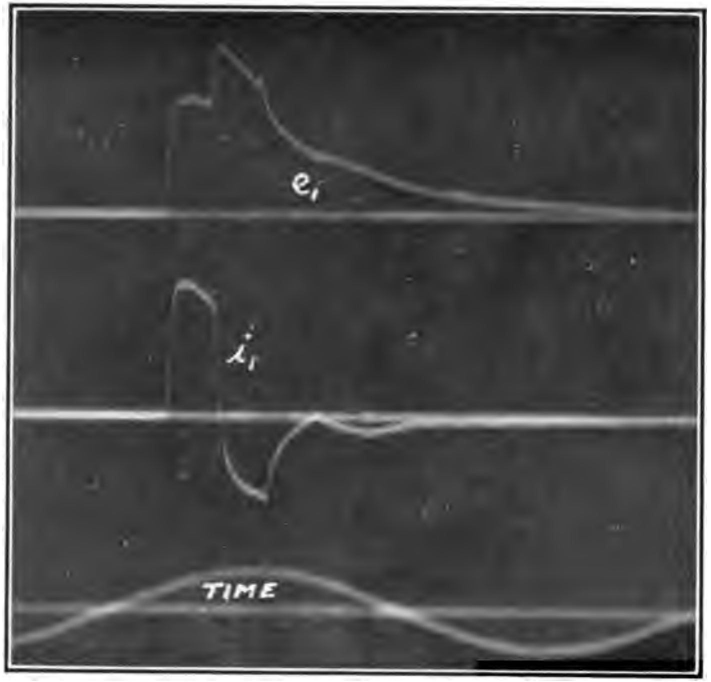
[3] See Steinmetz, "Engineering Mathematics", Chapter VI, section C.



[CUNNINGHAM AND DAVIS]

FIG. 12—VOLTAGE AND CURRENT AT GENERATOR END OF LINE
Showing reflection from open receiver end.

From these equations it follows that the total energy which traverses the line as a traveling wave is:

a. At the generator end

$$w_1 = 0.83 \text{ joules}$$

b. At the middle

$$w_2 = 0.72 \text{ joules}$$

c. At the receiving end

$$w_2 = 0.61 \text{ joules}$$

Some interesting conclusions may be drawn from the data and oscillograms shown.

1. The condition under which a condenser charge or discharge is oscillatory is

$$r^2 < \frac{4L}{C}$$

which is fulfilled by this line circuit, yet the transients are not oscillatory, but are steady exponential impulses. This shows that the above equation which divides the oscillatory from the gradual transients in a circuit containing massed resistance, inductance and capacity, does not apply to the line circuit with distributed resistance, inductance and capacity. This means that in a circuit with distributed constants, oscillatory and non-oscillatory transients can occur, and the nature of the transient, whether oscillatory or not, depends on the origin of the transient. This is in agreement with previous theoretical investigations.[4] Thus non-oscillatory single impulses may occur in transmission lines, cables, transformer windings, etc.

2. In Figs. 4 and 5 the current and voltage impulses coincide, and the magnetic and the dielectric components of the electric field reach their maxima simultaneously. That is, there is no surge of energy, but a steady propagation of energy along the circuit, or a traveling wave.

In the impulses considered in this paper we thus have the simplest and at the same time a typical case of a traveling wave; that is, a transient propagation of energy without oscillation, but with the current in phase with the voltage.

The other extreme is the stationary oscillation without propagation, or a typical standing wave, as it has frequently been recorded. In it the energy surges between the magnetic and the dielectric field, without any propagation of energy along the

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[4] Steinmetz, " Transient Phenomena and Oscillations ", p. 441.

circuit, and current and voltage are in quadrature with each other.

In the reflected impulse, like Fig. 12, propagation of energy as well as oscillation of energy occurs, and this oscillogram represents a combination of, or transition from the traveling wave to the stationary oscillation.

3. The second term of the exponential function represents the steepness of the wave front, and it is interesting to note that it seems to be greatest at the transition point between transformer and line, and apparently practically constant in the line at some distance from the transition point.

The most important conclusion which is evidenced by the results, as far as worked up, is that in the study of transient phenomena, circuits with distributed constants cannot be represented even approximately by equivalent circuits with massed constants, as it is customary and permissible to do in the study of permanent phenomena, but that in circuits with distributed capacity and inductance, transient phenomena occur which have no analogy in the transient phenomena of circuits with massed capacity and inductance.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

SOME MECHANICAL CONSIDERATIONS OF TRANSMISSION SYSTEMS

BY T. A. WORCESTER

In any transmission system each of its elements, the supporting structures, the insulators and conductors, has a vital mechanical function and on each may rest the success or the failure of the system. In the early days of high-voltage transmission these points were not given due consideration and there were many cases of the destruction of lines due to washouts, sleet and wind storms, and frequent breakages of wires due simply to contraction at low temperatures. During later years, however, engineers have profited by these experiences and a greater study has been made of the details of mechanical construction, resulting in the almost entire elimination of disasters, except in cases of most unusual and severe conditions.

The purpose of this paper is to review in a general way the stresses which must be considered in the various elements of a transmission system and to point out some of the means which have been resorted to to meet certain special conditions. Consideration will be given chiefly to steel tower structures, since they are by far the most important type of support for higher voltages. The wooden, steel and concrete poles have their field in the lower voltage range where they are able to compete against the builtup structure.

STRESSES

The stresses which a tower must be designed to withstand are (*a*) those acting in a vertical direction, due to the dead weight of the conductors and insulators, plus an allowance for ice covering; (*b*) in a horizontal direction at right angles to the line, due to wind pressure; (*c*) in a horizontal direction parallel to the line, due to wire breakages. All of these loads are applied at the ends of the crossarms, except a portion of (*b*) which is distributed over the entire tower.

The vertical load depends on the size, material and number of the conductors and ground wires, length of span and thickness of ice coating; the horizontal load at right angles to the line depends on these same elements, which determine the exposed surface, and the wind velocity; the horizontal load in the direction of the line depends on the size and number of conductors, the amount of ice and the number of wires which may break at any one time. Each of these governing factors will be briefly discussed.

The size of conductor depends on electrical considerations, except where the length of span is the governing feature.

The length of span, except in river or gorge crossings, is dependent upon the designer and must be chosen so as to give the line the least cost. As the span increases, the number of towers and insulators per mile decreases, but on the other hand the height of the towers must be increased to care for the greater sag, and at the same time they must be made proportionately stronger and heavier to care for the greater loads per span. The effect of these changes on the cost of a line is shown by the curve, Fig. 1.

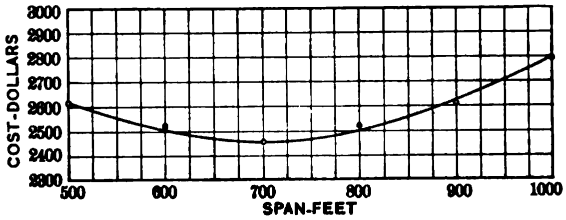


FIG. 1—COST PER MILE OF TOWERS AND INSULATORS, ERECTED.

The length of a span affects the loads in the vertical direction and in the horizontal direction across the line, and not that parallel to the line, since the latter is governed by the size of the conductor, it being necessary to adjust the sag so as not to exceed the safe stress for the wires.

For every size of conductor there is a practical limit of the length of span beyond which the sag and height of tower become excessive and there is danger of the wires swinging together. For the smaller sizes of conductor this limit is quite low (300 ft. (91 m.) for No. 4 B. & S. cable) and in many cases it will be found more economical to increase the size of conductor so as to permit using a greater span. The following tabulation illustrates this:

	Size of Conductor	Span feet	Sag feet	No. of towers per mile	Cost of towers and insulators per mile erected	Cost of wire and freight per mile	Total per mile
Case I.	No. 4 B.&S.	300	10.5	17.6	$3080	$322	$3402
Case II.	No. 2 B.&S.	360	10.5	14.7	2570	514	3084
					Saving per	mile............	$318

These figures are based on the assumption that the same towers and sags would be used in both cases, giving the same clearance to ground. The sag in Case I is the minimum sag at which wires may be strung on the basis of 0 deg. fahr., 8 lb. (3.6 kg.) wind, and ½ in. (1.27 cm.) sleet, and with these same conditions and sag the span for No. 2 wire is calculated and found to be 360 ft. (109 m.). With this tower spacing and No. 2 cable the cost of the line is $318 less than with No. 4 cable and 300 ft. (91 m.) span. It is allowable to assume that the same towers can be used in the second case as in the first, since the lightest tower which it is practicable to build would be sufficiently strong for the second case. However, it would be possible to put $20 more into the cost of each tower and still have the cost of the second line a trifle less than that of the first, and the gain would accrue from the electrical advantages of the larger size of conductor.

A span of 360 ft. (109 m.) is not necessarily the most economical span for the No. 2 conductor. Further calculation indicates that a 500-ft. (152 m.) span could be used with only a very slight increase in the cost of the towers. This limit cannot be extended beyond 500 ft. (152 m.), even though the line with greater spans would have a less cost. Here again the limit depends on mechanical considerations rather than on costs and is governed by the danger of lashing together of the wires in gusty winds.

In long spans over rivers, etc., the standard main line towers and conductors are frequently used. This practise may be permissible in some instances where the spans are not very much great erthan normal, but when the towers have been designed to meet closely the demands of the standard spacing it becomes dangerous to use them for any appreciably longer spans. It is advisable in these instances to use dead-end anchor towers with strain insulators and thus isolate the crossing span and prevent any trouble in other parts of the line from being carried into it.

For very long spans it is, of course, necessary to use conductors of greater mechanical strength than are used in the main part of the line and the supporting structures, must likewise be made correspondingly stronger. Too great care cannot be taken in planning such structures, as unusual stresses are likely to occur and would result seriously unless properly cared for. More than average allowances should be made for wind, sleet and temperature and a greater factor of safety should be used in the design of the steel work.

Ice and Wind

The amount of ice which may form on wires has been a much-discussed topic and one which will probably never be settled to the satisfaction of all concerned. However, the various engineering bodies have about agreed that it is safe to consider ½ in. (1.27 cm.) ice in conjunction with 8 lb. (3.6 kg.) wind pressure and 0 deg. fahr. as the worst combination of conditions likely to occur in the United States. It is conceded that there have been thicker formations of ice and greater wind pressures, yet the probability that they will occur simultaneously and with low temperature is so remote as to make it seem unnecessary to consider them. There is little doubt, however, that those engineers who have experienced destruction of their lines by sleet and wind storms will never use anything but the most conservative allowances. For spans crossing rivers, highways or railroads more liberal allowances are always made, the standard being ¾ in. (2 cm.) ice, 11 lb. (5 kg.) wind and 0 deg. fahr.

Ice and wind on the cables work together to increase all of the loads on a tower structure—the vertical load and the horizontal load in the direction of the line, by giving increased weight to the conductor, and the horizontal crosswise load by giving greater surface for the wind to act upon.

Wind on Towers

There is a great difference of opinion as to just how much wind pressure shall be allowed on the tower itself. It is certainly not sufficient to base this allowance on the same assumptions as are used for the conductors. Those assumptions are for wind velocities likely to occur simultaneously with heavy loading of ice and low temperature. Greater velocities may occur, independent of these last factors. It is, therefore, advisable to allow for at least the highest recorded value. This value, as indicated by the Government anemometer, is very nearly 100 mi. per hr., which corresponds to an actual velocity of 76.2 mi. per hr. and a pressure of 23.2 lb. per sq. ft. (113 kg. per sq. m.) ($0.004 \times V^2$ for flat surface). The government anemometer records the velocities only at intervals and does not give all instantaneous values, and these instantaneous values may be somewhat greater than those at the moment the record is taken, due to the gusty character of winds. It has been estimated that these gusts cause velocities 50 per cent greater than those which are recorded. Another feature enters, however, to counterbalance this effect, somewhat viz., the height above the earth surface. The anemometer records are taken well above the earth surface, while transmission structures are seldom higher than 75 ft. In consideration of these variables and uncertainties it is not possible to give one value of pressure to be used on all lines. A safe range of pressure, though, would be from 20 to 35 lb. per sq. ft. (97.5 to 170 kg. per sq. m.) depending on the general character of the country which the line traverses, *i.e.*, whether it is exposed to sweeping winds or protected.

It will usually be found that the maximum wind pressure acting on the bare towers and wires will have a greater overturning moment than that caused by the maximum wind assumed to accompany ice formation, acting on the ice-coated wires and towers, *i.e.*, the greater pressure due to the higher velocity of the wind, even though exerted on a smaller surface, will overbalance the less pressure acting on the greater surface. For this reason the side pressure on towers should be figured for both conditions and the design should be based on the loads caused by the worst of the two.

In calculating the wind on the towers the entire projected area of two lateral faces should be used as the surface over which the wind acts.

Wire Breakages

The most serious stresses which a transmission tower is called upon to withstand are those due to the breaking of conductors. Lines are put up with a view of not having the conductors break, but there are certain unavoidable conditions which frequently produce breaks. The most usual of these are (*a*) burning of the conductors due to short circuits or grounds started by lightning, large birds, swinging together of wires, etc., or through malicious intent; (*b*) breaking of conductors due to crystallization or fatigue of the metal produced by kinking during erection or by insufficiently rounded edges of cable clamps, and (*c*) by overloading of conductors during extreme conditions of temperature, wind, etc.

The causes in (*a*) have been overcome to a great extent by the use of various devices, principally the arcing ground suppressor, the ground ring and metal sleeve. The swinging together of conductors occurs only when light conductors are used in too long a span, where they will be likely to lash in the wind. Ordinarily in well designed spans the wires swing in unison so that there is no danger of their coming together.

The breaking of wires due to kinking is frequently not given due consideration and many lines erected by careless workmen have suffered from this cause. The elasticity and strength of the metal on the inside of the bend is decreased enormously by a short bend and when the wire is straightened out and drawn taught by frequent strains in the line it will finally weaken to the point of rupture. Likewise, many breaks have been caused by repeated bending of the conductor at the wire clamp on the pin type of insulator. The localization of the stress by a hard metal clamp finally makes the metal of the conductor brittle and rupture occurs well below the average tensile strength. A clamp may have well rounded edges and still cause trouble. It is the rigidity of the clamp, as well as too sharp an edge, which is harmful.

When all of the wires of a transmission line are intact there is no pull on the towers in the direction of the line (*i. e.*, on the intermediate towers, not the dead-end or other special structures). As soon, however, as a conductor is broken the strain which it took to cause the break is thrown on the adjacent towers. Obviously, therefore, the maximum load which the crossarm must stand in the direction of the line is equal to the tensile strength of the conductor which is used. For the smaller sizes of conductor this rule is usually observed, but for the larger sizes less liberal allowances are usually made. It is customary with the larger sized conductors to allow for a stress equal to one-half of the ultimate strength of the cables. This value is chosen since it is the maximum safe working stress, above which the cables are likely to stretch permanently.

With the suspension type of insulator the full length of an insulator string is thrown into the line when a break occurs and the strain in the conductor and on the crossarm is greatly reduced. But little consideration should be given to this fact, however, since there is a severe jerk when the insulator is drawn to its new position and the effect on the tower is not less and may be more than occurs when the pin type of insulator is used.

A question which naturally arises is how many conductors may break at any one time. This depends to a large extent on the cause of the breaks. If due to lightning or large birds it is probable that not more than one or possibly two conductors would break; but if due to poorly designed wire clamps, injury of wire during erection, or to excessive sleet and wind, it is conceivable that all might break. It is very rare, however, for all of the conductors to break, and further, it is hardly practicable to make such an assumption when considering main line towers, since it would raise the cost of the line to a prohibitive value. It is usual to compromise by allowing for the breakage of only two cables of a three- or six-conductor line and to safeguard the system by interposing anchor towers at frequent intervals. These anchor towers would be capable of withstanding the strains due to the breakage of all of the cables and would thus divide the line into isolated sections so that any trouble in one could not be communicated to the other.

In the rigid type of tower practically all of the stress caused by the breaking of several conductors is cared for by the tower itself, *i. e.*, the movement of the top of the tower is not sufficient to permit an even distribution of stress between the unbroken cables of the damaged span and those in the adjacent spans. With the flexible type of tower, however, the effect is different. The tower is designed to be rigid in the plane across the line and flexible in the direction parallel to the line, so that it will bend and allow an even distribution of stresses in the adjacent spans. For instance, consider a three-conductor system with one ground wire and assume that each cable has an ultimate strength of 6000 lb. (2721 kg.) and is strung to have a tension of one-half of its ultimate strength under the worst conditions likely to occur, and assume that these conditions prevail. Suppose that one of the conductors has been injured or is defective and that it breaks under this load. The tops of the towers on either side of the break will be pulled over by the four cables in the next span until the total tension in them would be just balanced by that in the remaining conductors of the damaged span.

This tension would amount to very nearly 12,000 lb. (5443 kg.), *i. e.*, 4000 lb. (1814 kg.) per cable, or 33 per cent more than the allowable stress. This load would not break the cables, but it would stretch them beyond the elastic limit and permanently weaken them.

Suppose that two cables had broken instead of one. Each of the remaining two would be strained with nearly 6000 lb. (2721 kg.), an amount almost equal to its ultimate breaking strength. The stress would not be quite 6000 lb. because the tension in the adjacent spans would decrease rapidly as the cables in the damaged span are stretched to greater length. However, the example serves to illustrate that it is necessary to use very much greater factors of safety in stringing conductors in a flexible tower system than would be used in a rigid system.

FOUNDATIONS

The foundations of a tower are of prime importance, yet under average normal conditions they offer but a small problem. In ordinary straight line work, over fairly level country, where the soil is hard or rocky and where the smaller sized conductors are used, no special foundations are necessary; the ground stub with cross piece or foot may simply be buried in the ground with a little rock filler, and if the spread of the tower legs is normal there is little to fear from tilting. With the larger sizes of conductor and longer spans the overturning moment frequently reaches such proportions as to make it advisable to use concrete foundations and thereby eliminate the need of spreading the tower legs an excessive amount. When towers must be placed where the soil is loose or marshy or where they may be endangered by floods or landslides it is essential that special consideration be given to the design of their foundations. It may be necessary to resort to any one of several types of construction: steel or timber piling, crib work, rock filling or concrete, or a combination of two or more of these. Fig. 4 shows one of the best types of foundation, used to meet a very special condition where it was necessary in order to gain entrance to a city to extend the right of way along the lake front and place the tower footings in the water.

Angle, hillside and anchor on long spans present serious problems from the foundation standpoint and must be carefully and liberally designed so as to allow no motion or slip whatever. It frequently pays to make a long detour in order to avoid bad hillsides or crumbly crests.

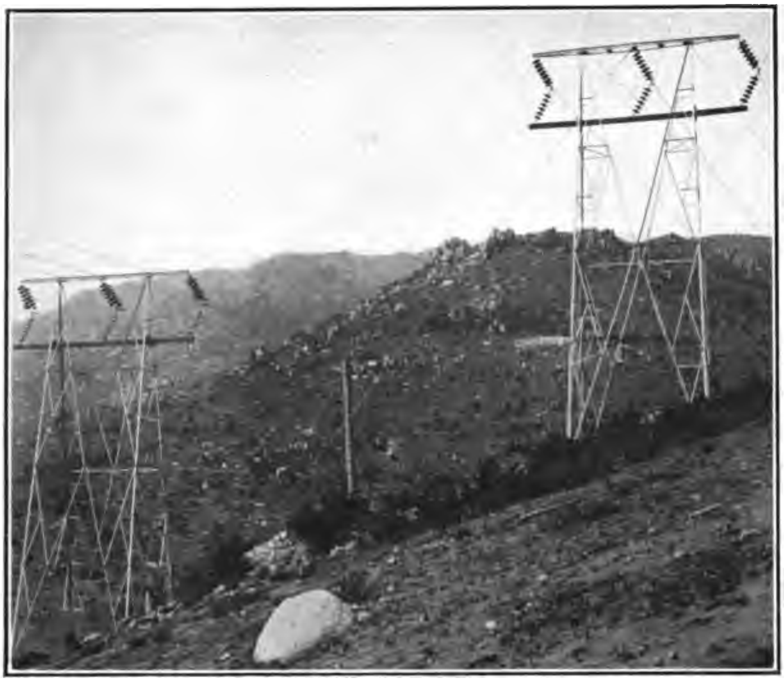


FIG. 2—DIFFICULT ANGLE AND HILLSIDE CONSTRUCTION. [WORCESTER]
Great Falls Water Power and Townsite Company.

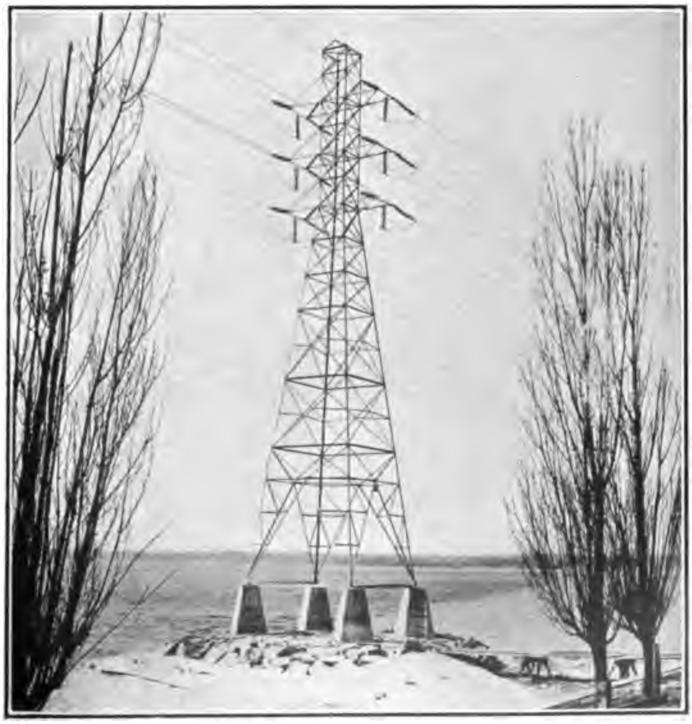
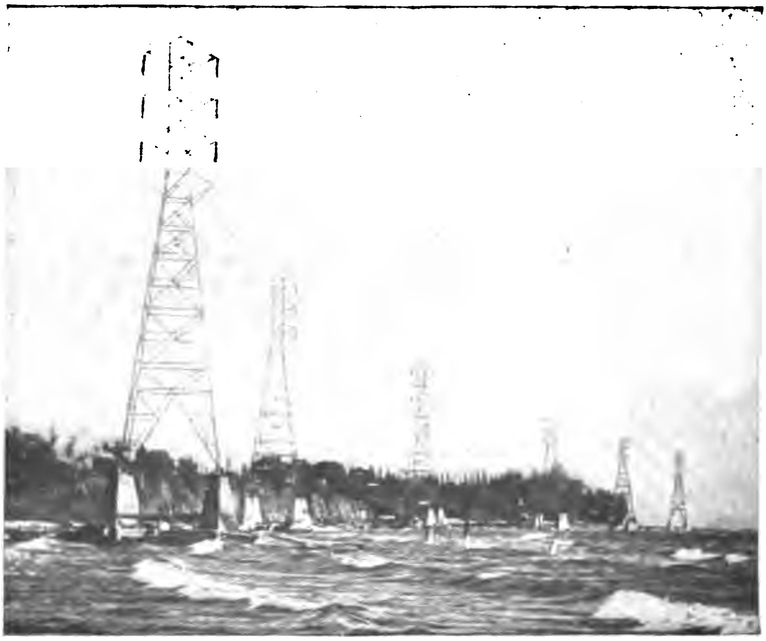
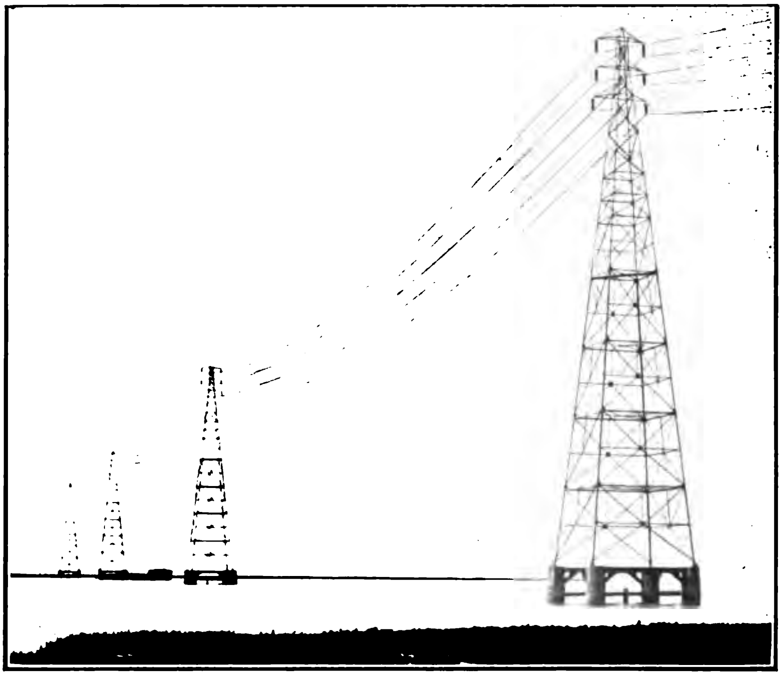


FIG. 3—INTERMEDIATE STRAIN ANCHOR TOWER. [WORCESTER]
Hydro-Electric Power Commission of Ontario.



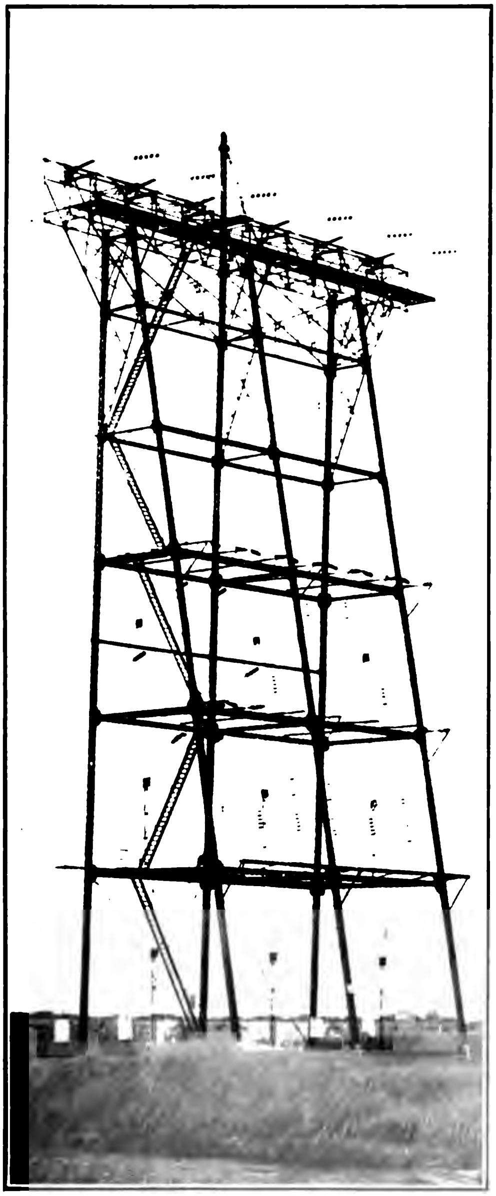
[WORCESTER]

FIG. 4—TRANSMISSION LINE ENTERING TORONTO.
Hydro-Electric Power Commission of Ontario.



[WORCESTER]

FIG. 5—STANDARD 50-FOOT TOWERS ON 87-FOOT LOWER EXTENSION—SPANS, 750 FEET.
Sierra and San Francisco Power Company's line crossing San Francisco Bay.



[WORCESTER]

Fig. 6—Long Span Strain Tower.
Great Western Power Company.
(Note balance weights to insure uniform tension in conductors.)

[WORCESTER]

Fig. 7—Flexible Tower Transmission Line.
Rochester & Sodus Bay Elec. Ry. Co.

It must be remembered that a very slight tilt at the base of the tower means large displacement at the top which may exert considerable extra tension in the conductors, and in the case of the suspension insulator may bring the conductors dangerously near the tower.

FACTORS OF SAFETY

In the design of all mechanical structures it is customary after assuming certain conditions of loading to allow a factor of safety; in other words, to design the parts so that their ultimate strength will be several times their assumed loading. The amount of this factor of safety depends on (*a*) the character of the load—whether steady, intermittent, or otherwise; (*b*) on the knowledge one has relative to the amount of load; (*c*) on the ease or difficulty of calculating the structure to care for the assumed loadings; (*d*) on the possibility of faults in construction, and (*e*) on the risk to life and property. In a transmission structure the load is intermittent and reversing and our knowledge as to its amount is not definite. These features tend to demand a relatively large factor of safety. However, this tendency is more than counterbalanced by the facts that it is not difficult to calculate the stresses when a definite load is assumed, that the chances for faults in manufacture are but few and that the risk to life and property is a minimum.*

Another feature which makes it possible to use a small factor of safety is that a sample tower may easily be tested with the assumed loadings and with ultimate breaking loads. Obviously if a factor of safety is used which will permit the tower to be strained with the assumed loads without being permanently deformed then such factor of safety will be satisfactory, provided the assumed loads correspond with the actual loads. The factor of safety for these conditions would be two if it is considered that the elastic limit of the metal is one-half of its ultimate strength. Many transmission towers have been built on this basis with a consequent saving in the cost of the line. On the other hand, more conservative engineers have used values of three and even four, these higher values being chosen to care for the uncertainty of load conditions. In one line recently built a factor of safety of four was used for all of the main line towers and three for all the strain or dead-end structures. This at first sight seems illogical, but it is justified, since the strain towers are figured for a very definite condition; *i. e.*, of all cables

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*Except at railroad and highway crossings, etc.

being broken in one span and with a maximum load of wind and ice on all those in the next span; whereas the intermediate towers are figured on an indefinite assumption; *i. e.*, of having only two cables break while the others are heavily loaded. The use of these large values, however, makes the cost of the line excessive, and for this reason it is common practise to use smaller values, two, two and one-half, or three for the intermediate towers and three or three and one-half for the strain towers. With this arrangement the main part of the line will be safe except in case of some unusual condition which produces worse loads than those assumed, and in event of such an accident the strain towers will prevent the trouble from traveling to the next section of the line.

For the conductors themselves a factor of safety of two is sufficient, except for very long spans and crossings, in which cases slightly larger values should be used unless a greater allowance is made for ice and wind than in other parts of the line. Larger factors of safety also must be used in conductors in flexible tower systems, as pointed out under " Wire Breakages. "

Flexible Towers

The flexible tower was discussed above with special reference to the stresses induced in the unbroken cables when one or two cables should break in one span, and it was found necessary to string the cables with less tension than in a rigid tower system. When this is done the flexible system immediately becomes mechanically stable and is of value. Economy is secured by the small weight and cost of the towers without unduly sacrificing the safety of the system.

A special field for the flexible tower appears to be for the higher voltage systems in which a double tower line of three conductors each is desired. There are a number of advantages in using such a system in preference to the six-conductor single tower system, the principal ones being that there is less liability to complete shut-down in case of accident to a tower and that there is greater safety for linemen when repairing damaged towers, conductors or insulators. The reason for the present limited use of double tower lines is the high cost of such a system when made up of the rigid type of tower. If engineers would look more into the possibilities and cost of the flexible structures there would undoubtedly be a more general use of double tower lines.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

ELECTRICAL CHARACTERISTICS OF THE SUSPENSION INSULATOR

BY F. W. PEEK, JR.

On the transmission line proper there are two electrical factors that fix the maximum voltage which may be used. First, the direct loss of energy into the air due to corona; second, arc-over or puncture of the line insulator.

The invention of the suspension insulator a few years ago went a great way toward eliminating the second factor. Transmission voltages were immediately raised to a point over 66,000 volts, where the corona factor began to be apparent practically, and seemed to be the limiting, or was, rather, the doubtful one. This led to very extensive investigations of the laws of corona formation and loss. The effect of corona can now be quite accurately pre-determined.

It seems probable that, with some exceptions, it will not be an electrical factor that eventually limits the voltage, but rather one of an economic nature. For instance, the power naturally concentrated at a given point, as in a waterfall, will generally be exceeded by the demand before the distance becomes so great that it is necessary to use voltages above the corona limit for economical transmission. Of course this does not mean that it is not necessary to consider the corona characteristics of the high-voltage transmission line, and to proportion the conductors properly for any given case. Consideration of corona characteristics is generally of importance in lines above 66,000 volts.

Although the suspension insulator, as at present designed, will be able to take care of transmission voltages for some time to come, it is important to look into the characteristics of the string of units in series with a view, possibly, of limiting line troubles, lessening the cost of line construction, etc.

In general, two arc-over voltages are specified in insulator tests: the rain arc-over voltage, and the dry arc-over voltage. For the same operating voltage, an insulator may give very good results, say in the Rocky Mountains, and not be satisfactory at all on the sea coast, due to surface leakage. This latter consideration, however, is beyond the scope of the present paper. The object of this paper is to show the general limiting features and characteristics of insulators in series, and the cause of these characteristics.

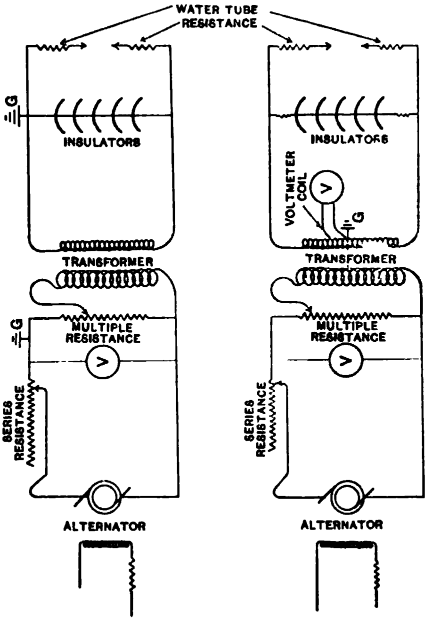

FIG. 1

METHOD OF TEST

The tests below were made on various sizes of insulators of different manufacture. Connections were as in Fig. 1. Voltage was gradually increased on a single insulator unit and gap setting until a dynamic arc followed, either at the gap, or over the insulator. If the arc took place at the gap first, new needles were placed in the gap and the distance between points was increased. This was repeated until the insulator arced over before the gap. Thus by a number of such settings the arc-over voltage of the insulator was determined. Units were then added, one at a time, and the arc-over voltages of different lengths of string were determined in a similar manner. Table I shows a typical data sheet and is self-explanatory.

TABLE I

DRY ARC-OVER TEST

Insulators in series	Gap inches	Arc-over at	Gap at arc over
1	8	Gap	
1	9	Insulator	
1	8.4	Gap	
1	8.6	Insulator	8.5
2	18	Insulator	
2	17	Insulator	
2	16	Gap	
2	17	Gap	
2	17	Insulator	17
3	21	Gap	
3	22	Gap	
3	25	Gap	
3	26	Insulator	
3	25.8	Gap	25.9

Temperature: Wet bulb.......20 deg. cent.
Dry " ....22 deg. cent.
Barometer 74 cm.

No special difficulty should be experienced in getting consistent test data if the proper precautions are taken, of which the most vital ones are:

1. The needle points should be at a distance at least equal to the length of the gap, preferably twice the length of the gap, away from walls, etc. New needles should be used after each arc-over.

2. Water tube resistances should be placed in series with each needle. The resistances should be of such value that the short-circuit current is between ½ ampere and one ampere. The principal object of the resistances is to eliminate the discrepancies that would otherwise arise, due to oscillations caused by the spark and the inductance and capacity of the leads.

3. Care should be taken not to use generator field control of the voltage over too great a range and thus cause disturbances due to wave distortion and the unstable condition of a weak field. The same applies to the transformer. The potentiometer method of voltage control is best for careful work. By the potentiometer method is meant a variable resistance in series with the generator

for voltage change, and a multiple resistance, taking from three to ten times the exciting current across the low-voltage winding of the transformer. (See Fig. 1.) The object of the multiple resistance is to prevent wave distortion that would otherwise be caused by the series resistance. The shunt and series resistances also tend to dampen disturbances. The potentiometer method combined with field control will generally be found most convenient. It is often desirable to place some resistance in series with the test piece. In doing this, however, due regard should be given the following precaution.

4. The power available at the test piece should be sufficient to allow a true dynamic arc to start before an appreciable change can take place in voltage or wave form. Often a white snapping arc will start across the gap without " dynamic " following. This should not count as a measurement, as it is generally caused by some disturbance.

5. The test piece should not be allowed to become warm by arcing.

6. Temperature, humidity, barometric readings, frequency, and size of needle should always be noted.

7. In rain tests, the character of spray, amount and resistance of water, etc., should be carefully noted.

TEST ELECTRICAL CHARACTERISTICS

Fig. 2 shows the wet and dry arc-over voltages for different numbers of insulators in series. These are characteristic curves of the suspension insulator. Considering the dry test: one unit arcs over at 85 kilovolts, two units arc over *not* at 85 × 2 or 170 kilovolts, but at 140 kilovolts. Seven units arc over not at 7×85 or 595 kilovolts, but at 335 kilovolts. Thus, we cannot say that if it takes e volts to arc over one insulator, it will take $n\,e$ volts to arc over n insulators. This is because the voltage along the string is not balanced, that is, the units do not share the voltage equally. The insulator next to the line takes more than its share and arcs over first, the others follow quickly in succession, and it generally appears as if the arc were simultaneous over the whole string. If voltage is gradually increased on a string of insulators in the dark, corona glow is first noticed around the cap on the line insulator, then as the voltage is gradually raised, corona appears successively on the second unit, third unit, etc., until arc-over occurs. It is also possible, at times, to get a "static snap " over the first insulator without arcing over the whole string. These tests show that the voltage is highest on the line insulator and gradually decreases on the units as the tower is approached. It is convenient in comparing the suitability of different types of units for connection together in a string to use the ratio of the actual arc-over voltage of *n* insulators to *n* times the arc-over voltage of one insulator. This may be called the ***string efficiency***. Thus

$$\text{string efficiency} = \frac{\text{arc-over voltage } n \text{ insulators}}{n \times \text{arc-over voltage one insulator}}$$

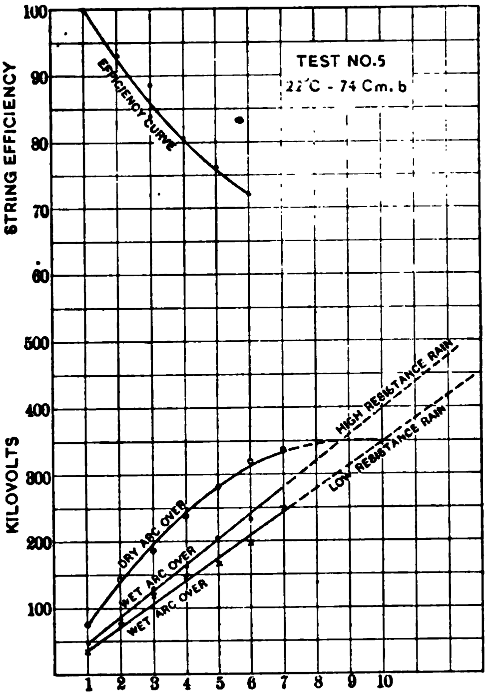

FIG. 2—TEST CHARACTERISTIC CURVES OF SUSPENSION INSULATORS.

The efficiency curve is plotted in Fig. 2, and shows that the ***string efficiency*** rapidly decreases as the length of the string is increased. If the units are very close together arc-over will take place from line to tower or over the whole string. This will mean a low efficiency, but not necessarily due to unbalance. A condition of this sort may sometimes be advantageous if balance is good.

The rain for the wet arc-over tests was obtained from nozzles that gave a heavy precipitation accompanied by a mist. The underside of the insulator was thus well dampened by the mist. The two rain curves show the difference due to the resistance of the water. There would probably be little difference in an arc-over test through a very wide range of conductivity of the water, with precipitation on top of the insulator only. With the above type of precipitation, however, where the insulator is dampened all over, the difference is marked. It is interesting to note the balancing effect the moisture has on the voltage

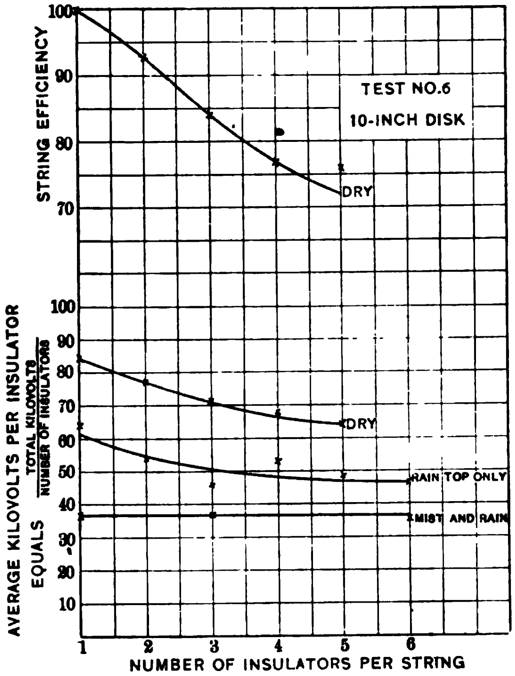

FIG. 3—TEST CHARACTERISTIC CURVES OF SUSPENSION INSULATORS

distribution. The wet arc-over voltage of *n* units in series is about equal to *n* times the arc-over voltage of a single unit. This would not be the case if only the top of each unit were wet, as is shown by test No. 6; plotted in Fig. 3. These curves are plotted with average volts per unit, that is, total arc-over volts divided by the number of units in series, as ordinates, and number of units in series as abscissas. The mist and rain curve where the insulator is wet all over shows that the voltage is balanced over each insulator. The curve for rain on top of insulator, only, shows unbalanced voltage similar to the dry test, except that the arc-over voltage is lowered. The moisture tends to balance the voltage because the leakage current is large compared with the capacity current. The action is somewhat similar to an auto-transformer across the string, with equal voltage taps connected to each unit. Note that due to the balancing, the wet and dry curves cross in Fig. 2, and that after a certain number of units are placed in series, the wet arc-over voltage is greater than the dry arc-over voltage.

TABLE II. ARC-OVER TESTS

TEST NO. 1. INSULATOR NO. 1

DRY

No. of insulators	Kilovolts	Per cent efficiency
1	52	100
2	89	85.6
3	132	84.7
4	175	84.2
5	215	82.7
6	259	83
7	277	76
8	308	74
9	340	72.6
10	...	.....

TABLE III

TEST NO. 2. INSULATOR NO. 2

DRY

No. of insulators	Kilovolts	Per cent efficiency
1	63	100
2	125	99.2
3	175	92.5
4	233	92.5
5	280	89.0
6	323	85.5
7	360	81.5

TABLE IV

TEST NO. 3. INSULATOR NO. 3

DRY

No. of insulators	Kilovolts	Per cent efficiency
1	68	100
2	132	97
3	193	94.7
4	245	90
5	295	86.8
6	324	79.5
7	357	74.9

TABLE V

Test No. 4. Insulator No. 4.

DRY

No. of insulators	Kilovolts	Per cent efficiency
1	82	100
2	146	89
3	212	86.2
4	258	78.6
5	308	75
6	355	72.2
7	...	....

TABLE VI

Test No. 5. Insulator No. 5

DRY

No. of insulators	Kilovolts	Per cent efficiency
1	74	100
2	137	93
3	186	84
4	238	80.5
5	281	76
6	318	72

TABLE VII

Test No. 5. Insulator No. 5

(HIGH-RESISTANCE RAIN WATER USED)

No. of insulators	Kilovolts
1	45
2	81
3	126
4	161
5	204
6	234
7	248

TABLE VIII

Test No. 5. Insulator No. 5

(LOW-RESISTANCE RAIN WATER USED)

No. of insulators per string	Total kilovolts
1	39
2	72
3	118
4	146
5	162
6	196
7	244

TABLE IX

Test No. 6. Insulator No. 6

No. of insulators in series	Total kilovolts				Average kilovolts		
	Dry	Wet	Mist	Efficiency dry	Dry	Wet	Mist
1	84	64	37	100	84	64	37
2	154	108		93	77	54	
3	212	138	111	84	71	46	37
4	262	212		77	68	53	
5	320	244		76	64	49	
6	...	284	214	...	..	47	36

Fig. 4 shows arc-over and efficiency curves made on different insulators, the relative sizes of which are shown in Fig. 5. Note that (2) is the most efficient insulator (dry), and will actually stand higher voltages after seven or eight insulators are placed in the string, than the larger units. The relative magnitude of mutual capacity c_2, and the capacity to ground c_1, for the caps, can be seen from Fig. 6. The cause of unbalancing of voltage will appear in the section on theoretical characteristics, and

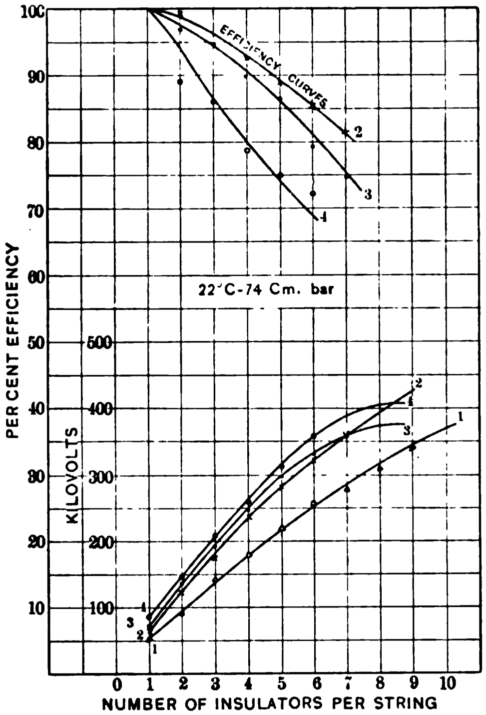

FIG. 4—TEST ARC-OVER AND EFFICIENCY CURVES FOR DIFFERENT SIZES AND TYPES OF INSULATORS.

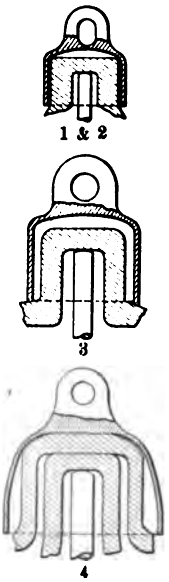

FIG. 6

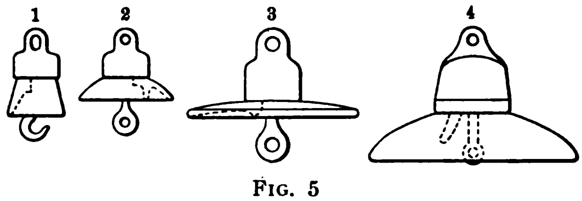

FIG. 5

depends upon the ratio $\frac{c_2}{c_1}$. It seems that where it is necessary to use an insulator with larger leakage surface than (2), as in a damp country, (3) or (4) would be more practical, but could probably be greatly improved by increasing $\frac{c_2}{c_1}$, perhaps by a different type of cap and metal parts, or better spacing of units. The general experience in practise is that the insulator next to the line is the one most frequently damaged by lightning, etc. The reasons for this are obvious from a consideration of the tests above, and the theoretical data below.

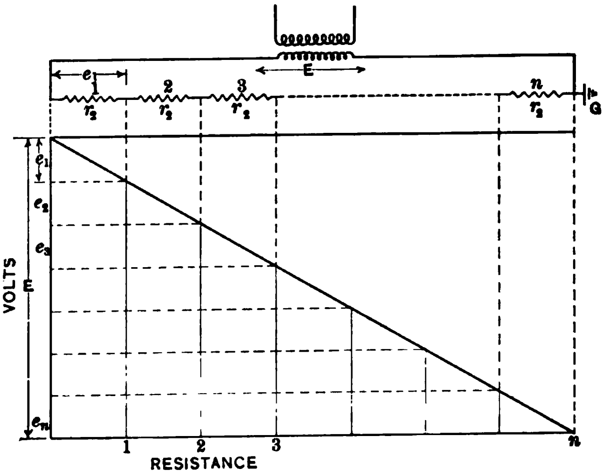

FIG. 7

THEORETICAL ELECTRICAL CHARACTERISTICS

If a number of equal resistances are connected in series in a string as in Fig. 7, and voltage E is applied across the string, the total current is

$$i_t = \frac{E}{n\, r_2}$$

The voltage across each resistance is equal and is

$$e_1 = e_2 \ldots\ldots\ldots\ldots = e_n = i_t\, r_2$$

And

$$E = ne_1 = ne_2 \ldots\ldots = ne_n$$

If, now, a number of equal resistances, r_1, to ground are added as in Fig. 8, the current through the first resistance r_2 is

$$(i_t - i_1)$$

and the voltage across the first resistance is

$$e_1 = (i_t - i_1)\, r_2$$

The voltages across the succeeding resistances are

$$e_2 = (i_t - i_1 - i_2)\, r_2$$

$$e_3 = (i_t - i_1 - i_2 - i_3)\, r_2$$

$$e_n = (i_t - i_1 - i_2 \ldots\ldots\ldots\ldots - i_n)\, r_2$$

It is seen at once that the voltage across the first resistance is greater than the voltage across the second, and so on. Also the greater the currents i_1, i_2, i_3, etc., are, the greater the unbalancing.

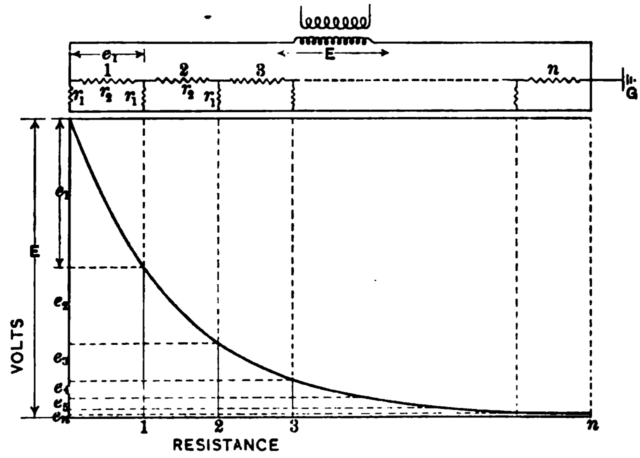

FIG. 8

A quite similar condition exists in a string of insulators,* except that the resistance must be replaced by capacitance. Let Fig. 9 represent a string of suspension insulators grounded at one end, *G*, as at the tower. It is seen that each insulator may be represented as a condenser with a capacity c_2, and that each connecting link and cap may be represented as a condenser with a capacity c_1 to ground. Greater capacity current passes through insulator (1) than through insulator (2), etc., hence, the voltage across insulator (1) is

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*The condition is also similar to that of the multigap lightning arreste which has already been discussed in the TRANSACTIONS.

greater than across insulator (2), etc., or, the voltage is not balanced along the string. The greater c_1 is, compared with c_2, the greater the unbalancing. Also, the greater the number of units in a string, the greater is the unbalancing. The voltage across the different insulators of a given string can be readily calculated at low and medium frequencies if the ratio $\frac{c_2}{c_1}$ is known, and it is assumed there is no surface leakage or corona. Leakage or corona will not appreciably affect the results at operating voltage.

Referring to Fig. 9, an expression for the total capacity of a string of n insulators may first be written.

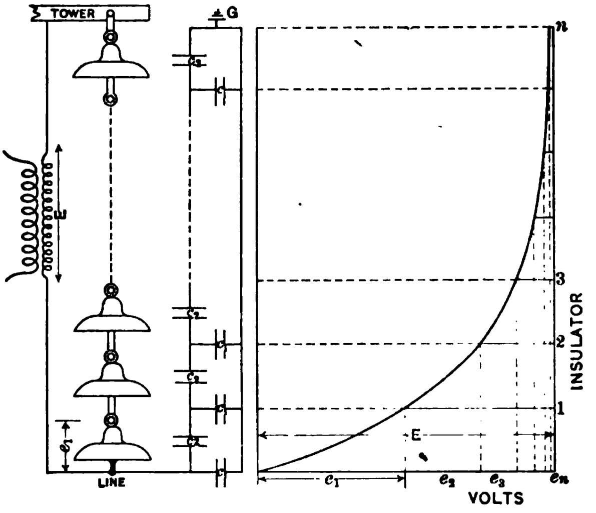


FIG. 9

Capacity of string

$$\text{Let } c_2 = x\, c_1$$

Then the total capacity for a string of n insulators is

One insulator

$$k_1 = c_1 + c_2 = c_1\,(1 + x)$$

Two insulators

$$k_2 = c_1 + \frac{1}{\frac{1}{c_1 + c_2} + \frac{1}{c_2}} = c_2\left(\frac{1}{x} + \frac{k_1}{c_2 + k_1}\right)$$

$$= c_1 + c_2 - \frac{c_2^2}{2\,c_2 + c_1}$$

Three insulators

$$k_3 = c_1 + \frac{1}{\dfrac{1}{k_2} + \dfrac{1}{c_2}} = c_2\left(\frac{1}{x} + \frac{k_2}{c_2 + k_2}\right)$$

$$= c_1 + c_2 - \frac{c_2^2}{c_2 + k_2} = c_1 + c_2 - \cfrac{c_2^2}{2c_2 + c_1 - \cfrac{c_2^2}{2c_2 + c_1}}$$

For a string of n insulators

$$k_n = c_1 + c_2 - \frac{c_2^2}{c_2 + k_{n-1}} = c_2\left(\frac{1}{x} + \frac{k_{n-1}}{c_2 + k_{n\;1}}\right)$$

$$= c_1 + c_2 - \cfrac{c_2^2}{2\,c_2 + c_1 - \cfrac{c_2^2}{2c_2 + c_1 - \cfrac{c_2^2}{2c_2 + c_1 - c_2^2 \cfrac{}{\cfrac{}{2c_2 + c_1}}}}}$$

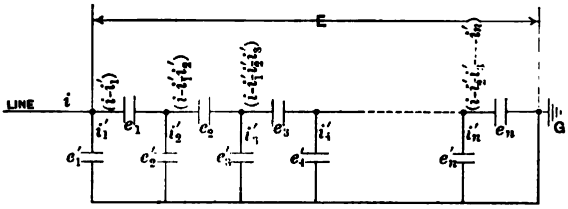


FIG. 10

The fraction to be carried out to $n - 1$, of the $(2c_2 + c_1)$ terms.

Voltage Distribution. Let E be the voltage across the string to ground. (See Fig. 10)

Also

i_t = total capacity current.

$x = \dfrac{c_2}{c_1}$ c_2 = mutual capacity
c_1 = capacity to ground

k_n = total capacity of the string.

$k = \dfrac{k_n}{c_1}$

Then
$$i_t = 2\,\pi f\,k_n\,E$$
$$i_1 = 2\,\pi f\,c_1\,E$$

Then the voltage across the first or line insulator is

$$e_1 = \frac{i_t - i_1}{2\,\pi f\,c_2} = \frac{2\,\pi f E\,(k_n - c_1)}{2\,\pi f\,c_2}$$

$$= E\,\frac{(k_n - c_1)}{c_2} = \frac{E}{x}\,(k - 1)$$

The voltage e_2 across the second insulator is found thus:

$$e_2' = E - e_1 = E\left(\frac{x - k + 1}{x}\right)$$

$$i_2 = 2\,\pi f\,e_2'\,c_1 = 2\,\pi f\,c_1\left(\frac{x - k + 1}{x}\right)E$$

Therefore

$$e_2 = \frac{(i_t - i_1 - i_2)}{2\,\pi f\,c_2} = E\,\frac{k(x + 1) - (2x + 1)}{x^2}$$

$$= \frac{E}{x}\left(k - 2 + \frac{k - 1}{x}\right) = e_1 - \frac{e_2'}{x}$$

For the third insulator

$$e_3 = E\,\frac{x\,(x + 1)\,(k - 1) + (2x + 1)\,(k - 1) - x\,(x + 1)}{x^3}$$

$$= \frac{E}{x}\left(k - 3 + \frac{3k - 4}{x} + \frac{k - 1}{x_2}\right) = e_2 - \frac{e_3'}{x}$$

For the *nth* insulator

$$e_n = \frac{E}{x}\left(k - n + \frac{\quad}{x} + \frac{\quad}{x_2} + \qquad + \frac{k - 1}{x^{n\ 1}}\right) = e_{n\ 1} - \frac{e_n'}{x}$$

Then we may write

$$e_1 = \frac{E}{x}\,(k - 1) \quad \text{first insulator}$$

$$e_2 = e_1 - \frac{e_2'}{x} = \frac{E}{x}\left(k - 2 + \frac{k - 1}{x}\right) \quad \text{second insulator}$$

$$e_3 = e_2 - \frac{e_3'}{x} = \frac{E}{x}\left(k - 3 + \frac{3k-4}{x} + \frac{k-1}{x_2}\right) \text{ third insulator}$$

$$e_4 = e_3 - \frac{e_4'}{x} = \frac{E}{x}\left(k - 4 + \frac{6k-4}{x} + \frac{5k-6}{x^2} + \frac{k-1}{x^3}\right)$$

fourth insulator

$$e_5 = e_4 - \frac{e_5'}{x} = \frac{E}{x}\left(k - 5 + \frac{10k-14}{x} + \frac{15k-15}{x^2} + \frac{7k-8}{x_3} + \frac{k-1}{x_4}\right)$$

$$e_n = e_{n-1} - \frac{e_n'}{x} = \frac{E}{x}\left(k-n+\frac{\quad}{x} + \frac{\quad}{x^2} + \ldots \frac{k-1}{x^{n-1}}\right)$$

From the above the following equations may be written for solving numerical problems.

Insulator Equations

Total capacity of a string of n insulators

$$1.\ k_n = c_1 + c_2 - \cfrac{c_2^2}{2c_2+c_1-\cfrac{c_2^2}{2c_2+c_1-\cfrac{c_2^2}{\cfrac{\quad}{\overline{2c_2+c_1}}}}}$$

Write fraction to $n - 1$ of the $2\,c_2 + c_1$ terms.

2. Volts across first or line insulator of string of n where E is the total string volts, is

$$e_1 = \frac{E}{x}(k-1)$$

$$k = \frac{k_n}{c_1}$$

3. The voltage across the mth insulator of a string of n is

$$e_m = e_{m-1} + \frac{e_{m-1} + e_{m-2} + \ldots\ldots\ldots\ldots + e_1 - E}{x}.$$

4.

$$E = \frac{e_1\,x}{k-1}$$

When the arc-over voltage of a single unit alone, e_a, is known

4a. $$E_a = \frac{e_a\, x}{(k - 1)} = \text{arc-over voltage of string.}$$

5. $$\text{String efficiency} = \frac{E_a}{n\, e_a} = \frac{x}{n\,(k - 1)}$$

For application of equations, see below.

CALCULATED CHARACTERISTICS

It is now interesting to calculate the characteristics of insulators in series, for different lengths of string, and different values of $\frac{c_2}{c_1}$, using formulas 1, 2, 3, 4, and 5.

TABLE X

Ratio c_2/c_1	1	2	5	10	15	20	50	100	500	1000
No. of insulators in series					Values	of k				
1	2.000	3.000	6.000	11.000	16.000	21.000	51.000	101.00	501.00	1001.00
2	1.667	2.200	3.728	6.238	8.742	11.244	26.247	51.21	251.25	501.25
3	1.625	2.048	3.135	4.842	6.387	8.197	18.998	34.89	173.22	334.89
4	1.619	2.012	2.927	4.263	5.546	6.814	14.350	26.87	126.87	251.87
5	1.618	2.003	2.846	3.988	5.049	6.083	12.172	22.20	102.20	202.20
6	"	2.001	2.814	3.851	4.777	5.676	10.777	19.19	85.83	169.29
7	"	2.000	2.801	3.781	4.623	5.421	9.863	17.15	74.36	145.82
8	"	"	2.795	3.743	4.574	5.265	9.238	15.69	65.68	128.18
9	"	"	2.793	3.724	4.505	5.178	8.797	14.63	59.03	114.63
10	"	"	2.792	3.713	4.465	5.108	8.481	13.85	53.85	103.85
11	"	"	"	3.708	4.447	5.069	8.251	13.23	49.68	95.09
12	"	"	"	3.705	4.415	5.044	8.083	12.84	46.22	91.85
13	"	"	"	3.703	4.411	5.036	7.958	12.52	43.29	81.75
14	"	"	"	3.702	4.409	5.024	7.865	12.33	40.93	76.58
15	"	"	"	3.702	4.407	5.015	7.796	12.17	38.81	72.21

To find the total capacity of the string, k_n, take the k above for the required ratio $\frac{c_2}{c_1}$, and the given number of insulators in series, and multiply by c_1.

$$k_n = k c_1$$

As an example of use of formulas, assume

$$\frac{c_2}{c_1} = \frac{5}{1} = x$$

$$n = 3 \qquad E = 100 \qquad k = \frac{k_n}{c_1}$$

From (1), $k_n = c_1 + c_2 - \cfrac{c_2^2}{2\,c_2 + c_1 - \cfrac{c_2^2}{2\,c_2 + c_1}}$

$$= 1 + 5 - \cfrac{25}{10 + 1 - \cfrac{25}{10 + 1}} = 1 + 5 - \frac{25}{11 - 2.27} = 3.135$$

From (2), $e_1 = \frac{E}{x}(k - 1)$

$$= \frac{100}{5}(3.135 - 1) = 42.7$$

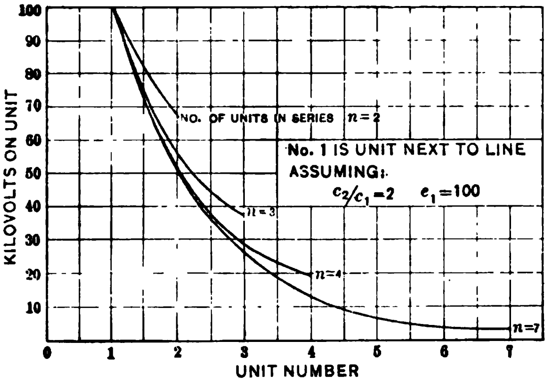


FIG. 11—CALCULATED VOLTAGE ACROSS DIFFERENT INSULATORS IN A STRING OF n UNITS.

From (3) $e_2 = e_{2\text{-}1} + \frac{e_{2\text{-}1} - E}{x} = e_1 + \frac{e_1 - E}{x}$

$$= 42.7 + \frac{42.7 - 100}{5} = 31.2$$

$$e_3 = \left(31.3 + \frac{31.3 + 42.7 - 100}{5}\right) = 26.1$$

$$E = e_1 + e_2 + e_3 = 100$$

Figs. 11 and 15 are calculated for 100 kilovolts, e_1, across the line insulator (1). Looking at Fig. 11, for a string of three insulators and the ratio $\frac{c_2}{c_1} = 2$,

$e_1 = 100$
$e_2 = 55$
$e_3 = 37$

Hence, the total voltage across the string is $e_1 + e_2 + e_3 = 192$. It is convenient to plot these curves so that e_1 is the arc-over voltage of a single unit, because when (1) in a given string is brought to its arc-over voltage, flash-over will take place and the other units follow in succession and complete arc-over occurs. Hence, if 100 kilovolts is the arc-over of a single unit alone, 192 is the arc-over voltage of the above string of three units. This can be calculated directly from equation (4a) and Table X, thus:

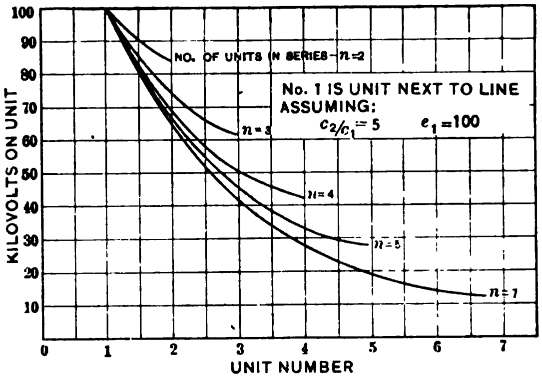


FIG. 12—VOLTAGE ACROSS DIFFERENT INSULATORS IN A STRING OF n UNITS.

$$E_a = \frac{e_a\, x}{(k-1)} = \frac{100 \times 2}{2.048 - 1} = 192$$

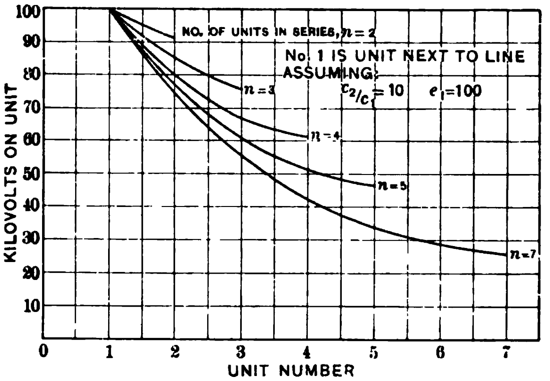


FIG. 13—VOLTAGE ACROSS DIFFERENT INSULATORS IN A STRING OF n UNITS.

The string efficiency, as defined under section on Test Characteristics, for the three units above, is

$$\text{Efficiency} = \frac{192}{3 \times 100} \doteq 0.64$$

The above curves may be used for finding the string arc-over for any other value than 100 for single unit arc-over, by reducing e_1, e_2, e_3, etc., in proportion.

Fig. 16 gives calculated values of total arc-over voltage for different numbers of insulators in series, and is similar to the test curves. Fig. 16 is obtained either by summation of e_1, e_2, ... e_n from Figs. 11 to 15, or by equation (4), and is based on 100 kilovolts arc-over for a single unit.

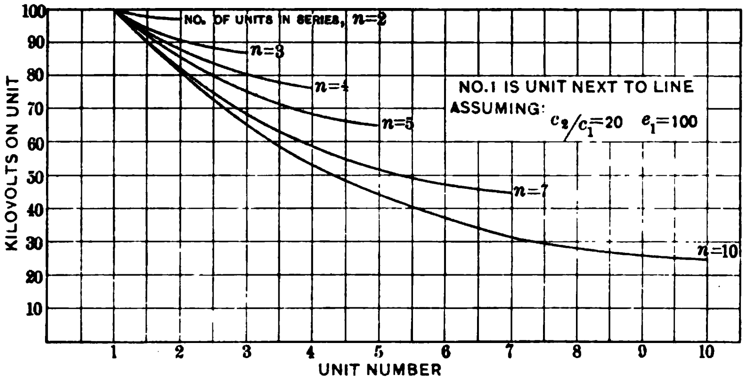


FIG. 14—VOLTAGE ACROSS DIFFERENT INSULATORS IN A STRING OF n UNITS.

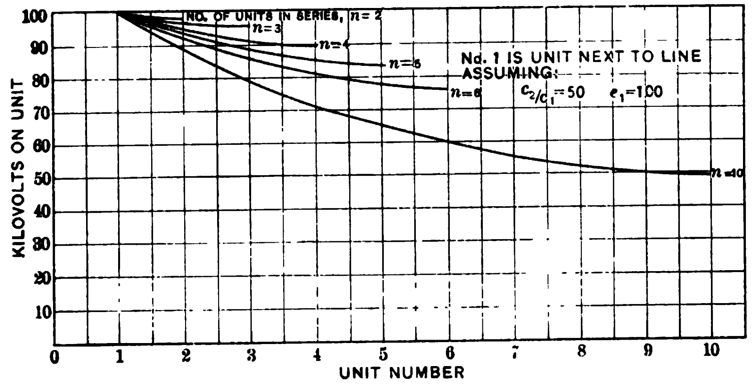


FIG. 15—VOLTAGE ACROSS DIFFERENT INSULATORS IN A STRING OF n UNITS.

Fig. 17 gives calculated efficiencies as defined above.

It is to be noted that while, theoretically, when reactance and resistance are not appreciable, frequency does not enter into the voltage distribution, at the high voltages where surface leakage or corona starts, and at arc-over, frequency would be a factor. Thus, for very long strings of small insulators it might be possible to arc over the insulators near the line without arcing over the whole string, due to the fall of potential over the arc resistance. This resistance would vary with the frequency. At very high frequency it is necessary to consider reactance. Before surface leakage starts, as at operating voltages, the distribution should be substantially as given in Figs. 11 to 15. As the voltage is increased, corona forms first on the line insulator, and probably, generally increases the mutual capacity c_2 without materially changing c_1. In this way a sort of automatic grading takes place, and the distribution by arc-over often indicates a much better distribution than exists at operating voltage. Hence, it seems that the arc-over would not always indicate the best insulators for all conditions of service. As, for instance, with surge, high-frequency oscillations, sudden impulse, lightning, or transient voltages, a bad operating distribution would probably mean not flash-over, but punctured porcelain, *i.e.*, the porcelain would puncture before corona could form to distribute the stress better. In selecting an insulator, therefore, it would probably be best to specify a certain arc-over voltage and string efficiency.

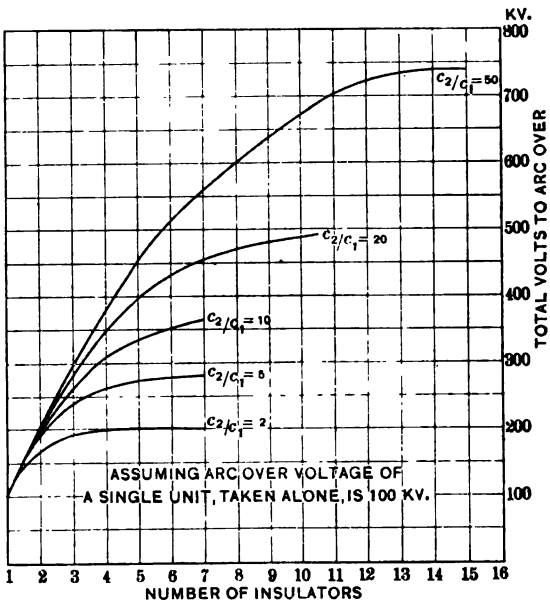


FIG. 16—CALCULATED ARC-OVER VOLTS OF *n* INSULATORS IN SERIES.

COMPARISON OF TEST CHARACTERISTICS AND THEORETICAL CHARACTERISTICS

In Fig. 18 the drawn curve is the theoretical one for $\frac{c_2}{c_1} = 50$, and the condition that a single unit arcs over at 63 kilovolts. This is the test arc-over voltage of a single unit in Test 2. The crosses are measured arc-over readings. The test values follow the theoretical curve rather better than would be expected, and seem to indicate little change in $\frac{c_2}{c_1}$ due to corona, and small leakage up to the flash-over point for this particular insulator.

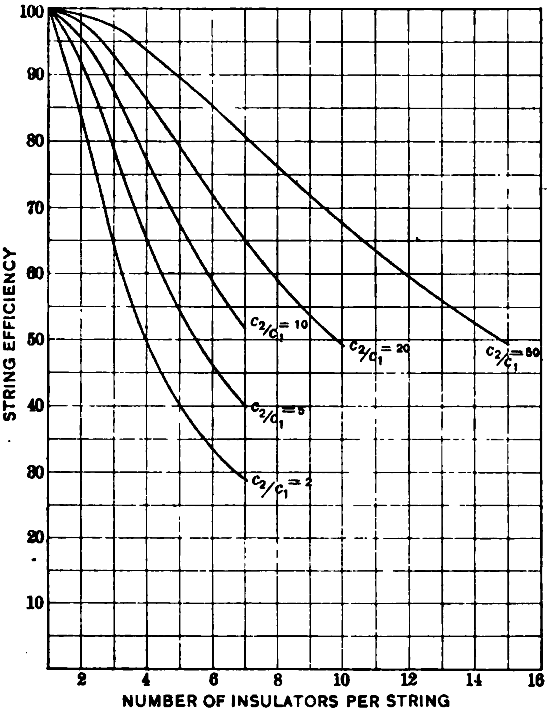


FIG. 17—CALCULATED STRING EFFICIENCY.

In Test 5 the arc-over voltage of a single unit is 74 kilovolts. The drawn curves in Fig. 19 are the theoretical ones for that condition, and $\frac{c_2}{c_1} = 10$, $\frac{c_2}{c_1} = 15$, and $\frac{c_2}{c_1} = 20$. The crosses are the measured values. This shows quite clearly the effect of automatic grading due to corona and leakage. For short strings the points follow the curve for $\frac{c_2}{c_1} = 10$, which, if continued, would give a very low flash-over efficiency. Automatic grading comes in and the points gradually shift up to the curve for $\frac{c_2}{c_1} = 20$. The actual value of $\frac{c_2}{c_1}$ under operating voltage is probably between 5 and 10. Thus, while arc-over tests for long strings may indicate a fair efficiency, the insulator is really operating at a very bad unbalance of voltage. This is further indicated by Fig. 20, for Test 4.

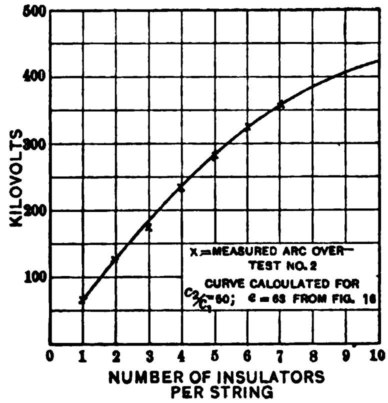


FIG. 18—COMPARISON OF CALCULATED CURVES AND TEST CURVES.

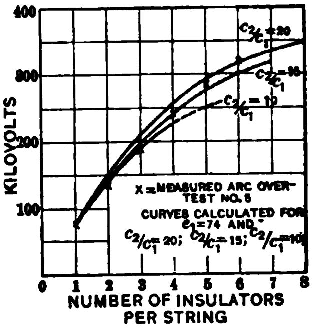


FIG. 19—COMPARISON OF CALCULATED CURVES AND TEST CURVES.

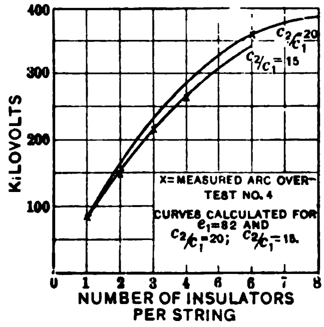


FIG. 20—COMPARISON OF CALCULATED CURVES AND TEST CURVES.

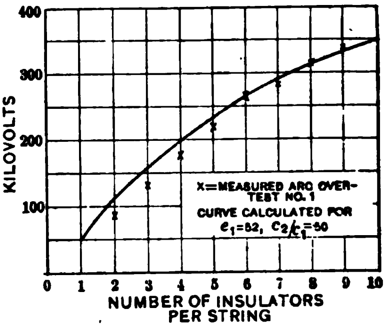


FIG. 21—COMPARISON OF CALCULATED CURVES AND TEST CURVES.

The theoretical curves given in Figs. 11 to 17 will be found useful in comparing and studying test values. For instance, the curves in Fig. 16 are calculated for total arc-over voltage of n insulators for different values of $\frac{c_2}{c_1}$, and arc-over voltage of 100 kilovolts for a single unit alone. Where the arc-over voltage of a single unit differs from 100 kilovolts, and is, say, 63 kilovolts, the curves may be used for graphical calculations by multiplying the ordinates by 0.63. The tabulated values of k may also be used for obtaining the string capacity k_n with minimum calculation.

CONCLUSIONS

1. An insulator taken as an individual unit may show very excellent characteristics, but, on account of certain inherent relations between mutual capacity and capacity to ground, be totally unfit for use in series.

2. The arc-over voltage test of insulators in series does not always indicate the best insulator, but should be supplemented by a study of corona formation in the individual units along the string. To this should be added a comparison of theoretical and arc-over efficiency curves.

3. Where the mutual capacity, c_2, is small compared with the capacity, c_1, to ground, after a certain number of insulators are added it is useless to increase the string length. For very high voltages insulation will probably not be obtained by long strings but rather by shorter strings of well-designed and properly spaced units; grading may also be resorted to. The arc-over voltage may often be actually increased in a given design by decreasing spacing between units. In selecting insulators, a good string balance or efficiency should be sought or specified. Without good balance the line insulator is likely to be punctured by lightning or surge.

4. The voltage balance along a string will be affected by the distance to the tower, etc.

5. The string arc-over voltage will generally decrease as the frequency is increased. It will also decrease as temperature is increased and barometric pressure is decreased.

6. The wet arc-over voltage will vary greatly with the resistance and temperature of the rain and the nature of the spray. The wet arc-over voltage may actually be greater than the dry arc-over voltage after a certain critical length of string is reached.

7. The arc-over test voltage on long strings will vary some-

what with the transformer connection, that is, whether one side of the transformer is grounded or not. One side of the transformer should be grounded to approximate practical conditions.

8. Insulator arc-over tests are valueless unless proper test precautions are taken to eliminate resonance, etc., and full data are given.

Thanks are due to Professor C. E. Magnusson of the University of Washington for his valuable assistance in the tests, equations and calculations, and to the Consulting Engineering Department of the General Electric Company for the facilities afforded.

DISCUSSION ON " COMPRESSION CHAMBER LIGHTNING ARRESTER AND THE PROTECTION OF DISTRIBUTION CIRCUITS " (CREIGHTON AND SHAVOR), " HUMAN ACCURACY: MULTI-RECORDER FOR LIGHTNING PHENOMENA AND SWITCHING " (CREIGHTON, NICHOLS AND HOSEGOOD), "STUDIES OF PROTECTION AND PROTECTIVE APPARATUS FOR ELECTRIC RAILWAYS " (CREIGHTON, SHAVOR AND CLARK), " PROPAGATION OF IMPULSES OVER A TRANSMISSION LINE " (CUNNINGHAM AND DAVIS), " SOME MECHANICAL CONSIDERATIONS OF TRANSMISSION SYSTEMS " (WORCESTER), AND " ELECTRICAL CHARACTERISTICS OF THE SUSPENSION INSULATOR " (PEEK); SCHENECTADY, N. Y., MAY 17, 1912.

E. M. Hewlett: I am naturally interested in the development of the suspension insulator, which I first brought before the Institute in 1907, at the Niagara Falls meeting. The suspension insulators in their present form are giving excellent service at 110,000 volts and 140,000 volts. Having increased the radius of distribution to more than twice that practicable with the 60,000-volt pin insulator, which seemed to be the limiting factor, we learn from the operating engineers that these insulators are giving satisfaction. The step to 110,000 volts was made with less line trouble than the previous step, due to the higher mechanical and electrical safety factors.

In the original design of the suspension insulator we did not realize what some of the factors that have since turned out to be a help to us, really were, that is, the higher safety factor and the opportunity to allow moisture to collect on both sides, and you will see that these have given us an insulator that under moist conditions will test up better than it does under dry conditions. Lightning generally comes during a rain storm, so our lightning troubles are likely to bother us less with the suspension insulator than if we had the pin insulator. Then the safety factor with the suspension insulator has been greater, and that probably explains the reason for less line trouble with the rise in voltage from 60,000 to 110,000 and to 140,000 volts. We know that Mr. Foot has been running his transmission line in Michigan at 140,000 volts for the last three months, and he says that everything is working very nicely indeed.

The mechanical safety factor of the suspension insulator has allowed or permitted construction on lower voltages, which is cheaper than the pin construction; that is, where a curve is made, or an anchorage is made, you can fasten the suspension insulator to the side of a pole, instead of on an arm, and it gives a very rugged and much simpler construction.

Since this paper was written tests have been made on suspension insulators of various makes, using a suitable transformer capable of delivering 750,000 volts. The curves between arc-over and number of units show only a slight falling off as the number of units is increased. This would indicate that the peculiar drooping characteristic is largely due to the capacity of the testing transformer.

It would seem from the above that there is still plenty of leeway above the present operating voltage (140,000 volts) before operating conditions will be affected by this phenomenon.

Paul M. Lincoln: I have been very much interested in the paper by Mr. Peek. He has brought out some points in that paper which are of great interest, and it is a line along which I have thought considerably myself. There is one point, however, to which I would call his attention, and that is, whether or not he has correctly analyzed the reason for the wet string of insulaators being of higher potential than the dry string.

There are two things which may be noted when a string of insulators becomes wet; first, the resistance of the path across the insulators is lowered. That is, as I understand Mr. Peek, the reason which he ascribes for the difference noted. There is, however, another effect which takes place when the insulator becomes wet, and that is an increase in the area of the conducting surfaces and a consequent change in the relation of the mutual capacity between adjacent disks to that of a disk to ground. It occurs to me it is that change in this relation of capacities that has the larger effect in enabling the wet string of insulators to stand a higher potential than the dry string.

That same consideration has led me, before, to believe that our insulator design for long strings might be made very much better by arbitrarily making the static capacity of those insulators which are next to the conductor higher than those which are nearer the tower. It is quite possible so to design a string of insulators that we change the static capacity of one against the other and make them such that the static potentials will be divided equally across the various insulators. It cannot be done when the mutual capacity is the same all through, but it is quite easy to design a string of insulators and change the static capacities, one against the other, so that the potential across the various insulators will be thereby more evenly divided.

Another point which may be mentioned in connection with the design of line insulators is the fact that on any section of an insulator the static strains at the inside are higher than they are at the outside. Reference to Fig. 6 of Mr. Peek's paper will show what I mean. The insulators partly shown in these sections are subjected to voltage strains which appear between a pin of relatively small diameter as one terminal and an enclosing metallic bonnet as the other.

Now, any one who is familiar with this matter knows at once that the strains across this individual section of a complete string of insulators are by no means evenly divided. The strains at the small diameter of the pin are much higher than they are at the large diameter of the enclosing cap, and here again, it seems to me, is an opportunity for considerable betterment in the design of insulators. In general, the diameter of the inside pin ought to be increased, and in some cases it would actually be possible, I believe, to reduce the static strains on that part of the insulation next to the small diameter pin by reducing the thickness of the insulating wall.

Referring to Mr. Worcester's paper, if I interpret it correctly, there are no conductors present, on the flexible towers he cites as an example, except the conductors which carry current. In the design of the flexible tower system I consider that the presence of an overhead ground wire will have a considerable bearing. The overhead ground wire has a double value in flexible tower systems. First, it gives the protection which is usually credited to it, of guarding against lightning, and secondly, it has very considerable bearing upon the design with reference to the strains on the wires when any conductor breaks. The ground wire in this case should be made of steel and should have a breaking strength considerably above that of any of the conductor wires which are used. By properly designing these and distributing them at the top of the tower, the condition which Mr. Worcester cites, that the strain on the conductors when one breaks goes considerably above the ultimate strength, does not necessarily follow, since a large part of the longitudinal strains may be taken by the ground wires.

Another point in that connection is the assumption many people make, that the straining of a conductor wire on a tower above its elastic limit is fatal. I do not believe this is the case. Any conductor or other piece of finished metal has been, in the process of its manufacture, continually subjected to such strains. Every wire that is rolled or drawn, during that process of rolling or drawing is subjected to strains beyond its elastic limit. If after it is up it is subjected to strains beyond its elastic limit, it does not mean, in my opinion, that the wire will be damaged; in fact, it is somewhat similar to the process of stretching and drawing, and it is quite conceivable that the wire, as a result of being subjected to strains above its elastic limit, is actually strengthened and not weakened.

R. J. McClelland: I wish to make a few remarks concerning Mr. Worcester's paper with special reference to the use of overhead ground wire as an additional support to the tower, both flexible and rigid, it being especially valuable for the former type.

In the design of a line using the so-called rigid tower, we have taken into consideration the additional support given to the structure by the overhead ground wire; this has consequently reduced the weight of the tower, and thereby decreased the cost of the line. Our experience has not yet indicated that we are in error in our assumptions; in fact, we had an experience which tends to bear out our conclusion.

A 100-kv. double circuit steel tower line constructed last year with six No. 0 conductors and ⅜-in. (9.5 mm.) galvanized steel strand as overhead ground wire, was wrecked. The circumstances were as follows: the line was completed before the right-of-way was thoroughly cleared, and during a very severe wind storm, a tree was blown into the line, breaking five of the No. 0 conductors. The towers suffered no damage whatsoever. We believe that this fact was due to two reasons:

1. The overhead guard or ground wire. The towers were very recently erected, and we did not consider that the anchorage was first-class; in fact, there had been more or less rain and the ground was not settled around the steel footings, no concrete being used.

2. The strain on the tower was very greatly relieved due to the slack put into the line by the suspension insulators. In this case we had six units, which means that there was slightly over four ft. (1.2 m.) between the crossarm and the wire, the major portion of which, especially at the first tower, was put into the line, thus relieving the strain on the tower to a very great extent. This is transmitted back, of course, to the succeeding towers, to a lesser degree.

It would seem that this last fact has not been given sufficient consideration in connection with either the rigid or flexible tower transmission line construction, and that by taking these two important points into consideration, it should be possible to reduce test loads usually called for in tower design, thereby reducing the cost of construction.

C. Edward Magnusson: I have received a paper from Mr. Andrew McNaughton, of McGill University, giving the results of an investigation of string insulators which he has recently completed. This paper I wish to present in connection with the discussion of Mr. Peek's paper, as it gives additional data of considerable importance. The theoretical calculations have been made on a somewhat different basis, and present the problem from another point of view. The experimental data are in full accord with the results presented by Mr. Peek, and form an excellent check on the work described in the latter's paper.

Andrew McNaughton (by letter): The object of this paper is to calculate the potential distribution over suspension type insulators and to compare the resulting theoretical flash-over voltages with those actually obtained under test.

In the calculation of the potential distribution regard must be given to the following:

(a) Resistance of the material of the insulator.
Leakage over the surface.
(b) Capacity of a single unit.
Extra capacity between units when two or more are in series.
(c) Voltage, in its effect on capacity and surface resistance, due to formation of corona.
(d) Frequency, as affecting the critical point of corona forma-

tion and the distribution of stress between resistances and capacities in series.

Consider the case where the conductance is so small in comparison to (capacity) × (voltage) × (frequency) that its effect on the potential distribution may be neglected. At voltages below that of corona formation the string of insulators may be regarded as equivalent to a system of capacities C_1, C_2...... C_n, as shown in Figs. 1-5, where

C_1 is the capacity of a single unit.
C_2 is the extra capacity over two units.
....
C_n is the extra capacity over n units.

If the various capacities C_1 C_2.... C_n are known, the potential distribution may be calculated.

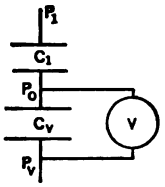


FIG. 1

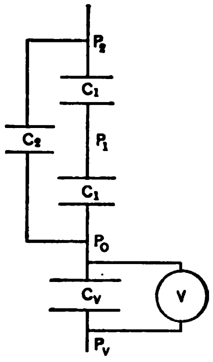


FIG. 2

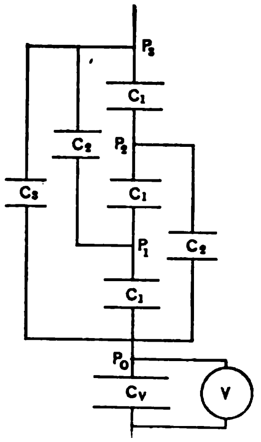


FIG. 3

Fig. 1 shows the diagram of connections used in determining C_1. An electrostatic voltmeter V is shunted across a known capacity C_v which is in series with the insulator unit of capacity C_1, and an alternating voltage is applied to the circuit. The resulting potentials are represented by P_v, P_0 and P_i.

Then

$$(P_1 - P_0) = (V_0) - (P_0 - P_v) \qquad (1)$$

where V_0 is the transformer voltage

$(P_1 - P_0)$ is voltage across capacity C_1

$(P_0 - P_v)$ is voltage across capacity C_v

Equating the charge at P_0 to zero,

$$(P_0 - P_1)\,C_1 + (P_0 - P_v)\,C_v = 0 \qquad (2)$$

and

$$C_1 = \frac{(P_0 - P_v)}{(P_1 - P_0)}\,C_v \qquad (3)$$

Fig. 2 shows the arrangement with two units. Capacities C_1 and C_2 are involved.

Equating charge at P_0 to zero,

$$(P_0 - P_2)\left(\frac{C_1}{2} + C_2\right) + (P_0 - P_v)\,C_v = 0 \qquad (4)$$

and

$$C_2 = \frac{(P_0 - P_v)}{(P_2 - P_0)}\,(C_v) - \left(\frac{C_1}{2}\right) \qquad (5)$$

Fig. 3 corresponds to three units in series.

Equating charge at P_1 to zero,

$$(P_1 - P_0)\,C_1 + (P_1 - P_2)\,C_1 + (P_1 - P_3)\,C_2 = 0 \qquad (6)$$

and by symmetry

$$(P_1 - P_0) = (P_3 - P_2) \qquad (7)$$

Eliminating P_2 between equations (6) and (7) gives

$$(P_1 - P_0)\,C_1 + (P_1 - P_3 + P_1 - P_0)\,C_1 + (P_1 - P_3)\,C_2 = 0$$

Collecting terms,

$$(P_1 - P_0)\,(3\,C_1 + C_2) = (P_3 - P_0)\,(C_1 + C_2) \qquad (8)$$

from which

$$\frac{P_1 - P_0}{P_3 - P_0} = \frac{C_1 + C_2}{3\,C_1 + C_2} \qquad (9)$$

and

$$\frac{P_2 - P_0}{P_3 - P_0} = 1 - \frac{C_1 + C_2}{3\,C_1 + C\,2} \qquad (10)$$

Now equating the charge at P_0 to zero,

$$(P_0 - P_v)\,C_v + (P_0 - P_1)\,C_1 + (P_0 - P_2)\,C_2 + (P_0 - P_3)\,C_3 = 0 \qquad (11)$$

and

$$C_3 = \frac{P_0 - P_v}{P_3 - P_0} C_v + \frac{P_0 - P_1}{P_3 - P_0} C_1 + \frac{P_0 - P_2}{P_3 - P_0} C_2 \qquad (12)$$

Fig. 4 corresponds to four units in series.
By symmetry

$$P_2 - P_0 = \frac{P_4 - P_0}{2} \qquad (13)$$

$$P_3 - P_0 = P_4 - P_1$$

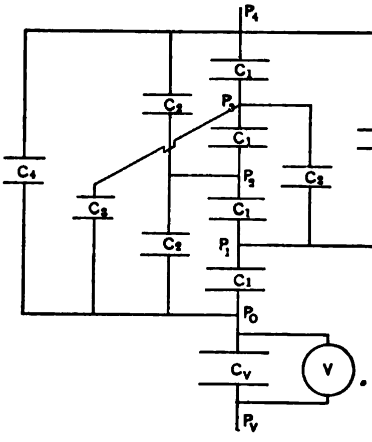


FIG. 4

and equating the charge at P_1 to zero,

$$(P_1-P_0)\,C_1+(P_1-P_2)\,C_1+(P_1-P_3)\,C_2+(P_1-P_4)\,C_4=0 \qquad (14)$$

Eliminating P_2 and P_3 between equations (**13**) and (**14**), and reducing,

$$(P_1 - P_0)\,(2C_1 + 2C_2 + C_3) = (P_4 - P_0)\left(\frac{C_1}{2} + C_2 + C_3\right) \qquad (15)$$

whence

$$\frac{P_1 - P_0}{P_4 - P_0} = \frac{\frac{C_1}{2} + C_2 + C_3}{2\,C_1 + 2\,C_2 + C_3} \qquad (16)$$

Equating the charge at P_0 to zero,

$$(P_0 - P_v)\,C_v + (P_0 - P_1)\,C_1 + (P_0 - P_2)\,C_2 \\ + (P_0 - P_3)\,C_3 + (P_0 - P_4)\,C_4 = 0 \quad (17)$$

and therefore

$$C_4 = \frac{P_0 - P_v}{P_4 - P_0}\,C_v + \frac{P_0 - P_1}{P_4 - P_0}\,C_1 \\ + \frac{P_0 - P_2}{P_4 - P_0}\,C_2 + \frac{P_0 - P_3}{P_4 - P_0}\,C_3 \quad (18)$$

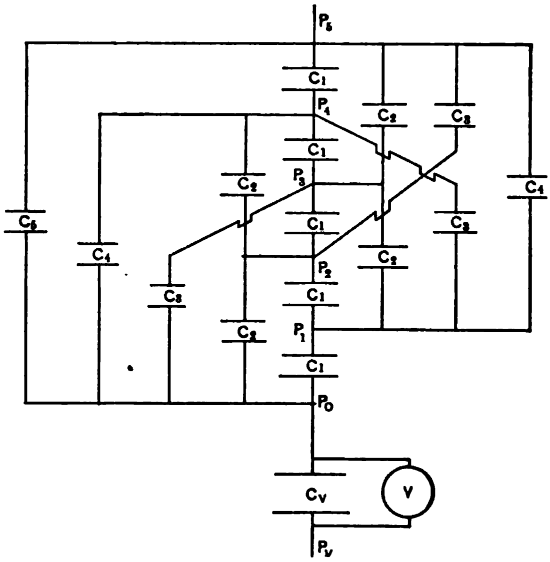


FIG. 5

Fig. 5 corresponds to five units.

By symmetry

$$(P_4 - P_0) = (P_5 - P_1) \\ (P_3 - P_0) = (P_5 - P_2) \quad (19)$$

and, equating the charge at P_1 to zero,

$$(P_1 - P_0)\,C_1 + (P_1 - P_2)\,C_1 + (P_1 - P_3)\,C_2 + \\ (P_1 - P_4)\,C_3 + (P_1 - P_5)\,C_4 = 0 \quad (20)$$

Eliminating P_3 and P_4 between equations (**19**) and (**20**), and reducing,

$$(P_1 - P_0)(2C_1 + C_2 + 2C_3 + C_4) = (P_2 - P_0)(C_1 - C_2) + (P_5 - P_0)(C_2 + C_3 + C_4) \qquad \textbf{(21)}$$

Similarly, by equating charge at P_2 to zero and eliminating P_3 and P_4 by equation (**19**),

$$(P_2 - P_0)(3C_1 + 2C_2 + C_3) = (P_1 - P_0)(C_1 - C_2) + (P_5 - P_0)(C_1 + C_2 + C_3) \qquad \textbf{(22)}$$

Combining equations (**21**) and (**22**),

$$\frac{P_1 - P_0}{P_5 - P_0} = \frac{\dfrac{(C_1 - C_2)(C_1 + C_2 + C_3)}{(3C_1 + 2C_2 + C_3)} + (C_2 + C_3 + C_4)}{(2C_1 - C_2 + 2C_3 + C_4) - \dfrac{(C_1 - C_2)^2}{(3C_1 + 2C_2 + C_3)}} \qquad \textbf{(23)}$$

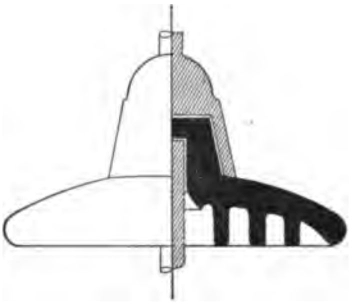


FIG. 6

$$\frac{P_2 - P_0}{P_5 - P_0} = \frac{\dfrac{(C_1 - C_2)(C_2 + C_3 + C_4)}{(2C_1 + C_2 + 2C_3 + C_4)} + (C_1 + C_2 + C_3)}{(3C_1 + 2C_2 + C_3) - \dfrac{(C_1 - C_2)^2}{2C_1 + C_2 + 2C_3 + C_4}} \qquad \textbf{(24)}$$

Equating the charge at P_0 to zero,

$$(P_0 - P_v)\,C_v + (P_0 - P_1)\,C_1 \ldots . (P_0 - P_5)\,C_5 = 0 \qquad \textbf{(25)}$$

whence

$$C_5 = \frac{P_0 - P_v}{P_5 - P_0} C_v + \frac{P_0 - P_1}{P_5 - P_0} C_1 + \ldots . \frac{P_0 - P_4}{P_5 - P_0} C_4 \qquad \textbf{(26)}$$

Similarly, for six units:
By symmetry

$$\begin{aligned} P_5 - P_0 &= P_6 - P_1 \\ P_4 - P_0 &= P_6 - P_2 \\ P_3 - P_0 &= \frac{P_6 - P_0}{2} \end{aligned} \tag{27}$$

and, equating charge at P_1 to zero,

$$(P_1 - P_0)\, C_1 + (P_1 - P_2)\, C_1 + (P_1 - P_3)\, C_2 \ldots . (P_1 - P_6)\, C_5 = 0 \tag{28}$$

Eliminating P_3, P_4 and P_5 between equations (27) and (28), and reducing,

$$\begin{aligned} (P_1 - P_0)\,(2\,C_1 + C_2 + C_3 + 2\,C_4 + C_5) &= (P_2 - P_0)\,(C_1 - C_3) \\ &\quad + (P_6 - P_0)\left(\frac{C_2}{2} + C_3 + C_4 + C_5\right) \end{aligned} \tag{29}$$

Equating the charge at P_2 to zero,

$$\begin{aligned} (P_2 - P_0)\, C_2 + (P_2 - P_1)\,(C_1) + (P_2 - P_3)\,(C_1) + (P_2 - P_4)\, C_2 \\ + (P_2 - P_5)\, C_5 + (P_2 - P_6)\, C_4 = 0 \end{aligned} \tag{30}$$

and, eliminating P_3, P_4 and P_5 by equation (27),

$$\begin{aligned} (P_2 - P_0)\,(2C_1 + 3C_2 + C_3 + C_4) &= (P_1 - P_0)\,(C_1 - C_3) \\ &\quad + (P_6 - P_0)\left(\frac{C_1}{2} + C_2 + C_3 + C_4\right) \end{aligned} \tag{31}$$

Eliminating P_2 or P_1 between equations (29) and (31),

$$\frac{P_1 - P_0}{P_6 - P_0} = \frac{\dfrac{(C_1 - C_3)\left(\dfrac{C_1}{2} + C_2 + C_3 + C_4\right)}{(2\,C_1 + 3\,C_2 + C_3 + C_4)} + \left(\dfrac{C_2}{2} + C_3 + C_4 + C_5\right)}{(2\,C_1 + C_2 + C_3 + 2\,C_4 + C_5) - \dfrac{(C_1 - C_3)^2}{(2\,C_1 + 3\,C_2 + C_3 + C_4)}} \tag{32}$$

and

$$\frac{P_2 - P_0}{P_6 - P_0} = \frac{\dfrac{(C_1 - C_3)\left(\dfrac{C_2}{2} + C_3 + C_4 + C_5\right)}{(2\,C_1 + C_2 + C_3 + 2\,C_4 + C_5)} + \left(\dfrac{C_1}{2} + C_2 + C_3 + C_4\right)}{(2\,C_1 + 3\,C_2 + C_3 + C_4) - \dfrac{(C_1 - C_3)^2}{(2\,C_1 + C_2 + C_3 + 2\,C_4 + C_5)}} \tag{33}$$

Now equating the charge at P_0 to zero,

$$(P_0 - P_v)\, C_v + (P_0 - P_1)\, C_1 + \dots\dots (P_0 - P_6)\, C_6 = 0 \qquad \textbf{(34)}$$

whence

$$C_6 = \frac{P_0 - P_v}{P_6 - P_0}\, C_v + \frac{P_0 - P_1}{P_6 - P_0}\, C_1 \dots\dots \frac{P_0 - P_5}{P_6 - P_0}\, C_5 \qquad \textbf{(35)}$$

In like manner for seven or more units the capacity and potential coefficients may be derived and hence the potential distribution calculated.

Fig. 7 gives the results of a set of observations taken on units similar to that shown in Fig. 6.

The frequency was 53 ~ per sec.

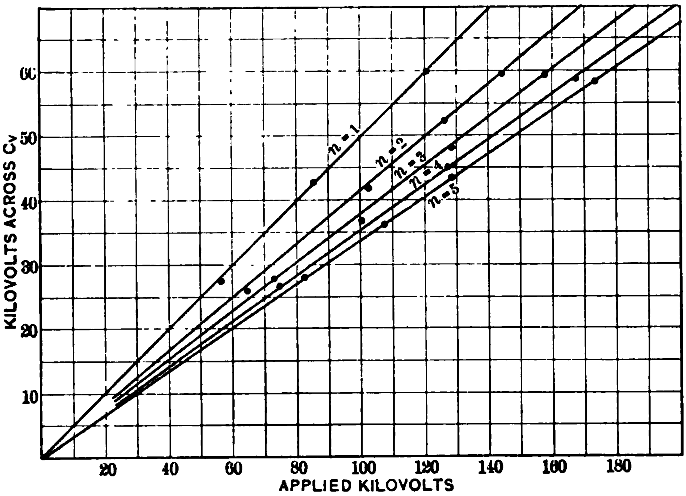


Fig. 7—Volts across C_v with n Units in Series

The voltage was controlled by resistance in the alternator field and measured by the auxiliary coil method and by electrostatic voltmeter.

Fig. 8 gives the calculated capacity coefficients.

Fig. 9 shows the resulting potential distribution over the units in strings of different lengths.

The ordinates represent percentages of what the stress would be if it were uniformly distributed. For example, in a string of four units the stress on the end unit is 130 per cent, on the second unit is 70 per cent, on the third unit 70 per cent, and on the fourth or other end unit 130 per cent.

Fig. 10 gives the calculated flash-over voltage on the assumption that the failure of a string occurs at the same stress on the

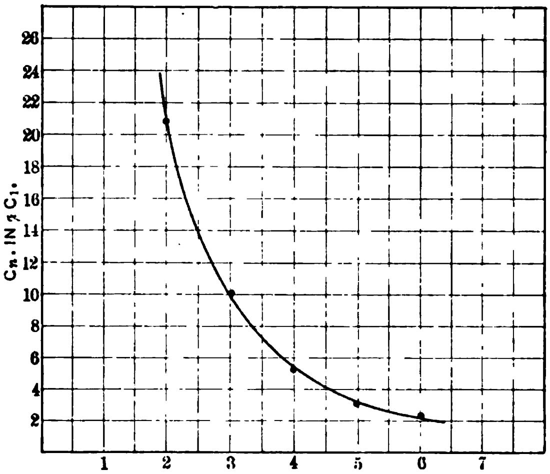


FIG. 8

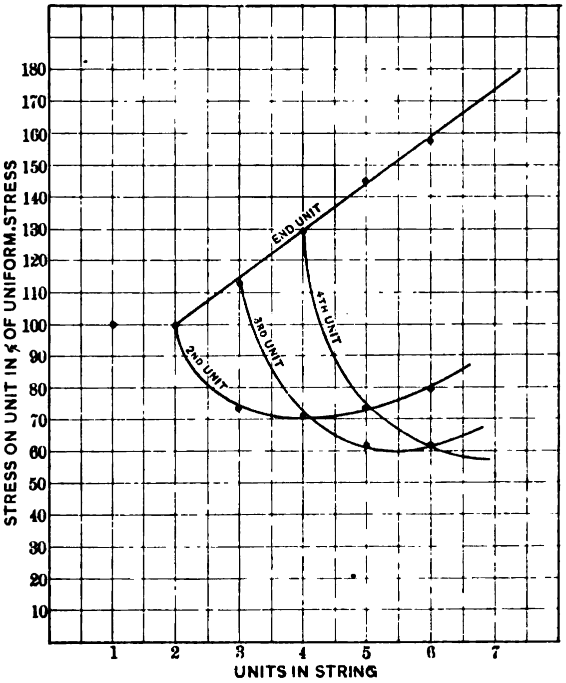


FIG. 9—POTENTIAL DISTRIBUTION

end unit in each case, that is, the breakdown of the end units causes the remainder to fail by concentrating on them nearly the whole of the voltage.

The units in strings of two or three fail by flash-over of the insulator as a whole, and this occurs at a lower value of voltage than that corresponding to successive breakdown. The test points lie below the calculated.

With four units, Figs. 11, 12 and 13 show failure both by successive discharge and by air arcing. At this number of units the calculated and test curves cross.

With five or more units the failure is due to the unbalanced potential distribution, that is, to successive discharge, and occurs at a higher voltage than calculated, because of the auto-grading of capacity produced by corona.

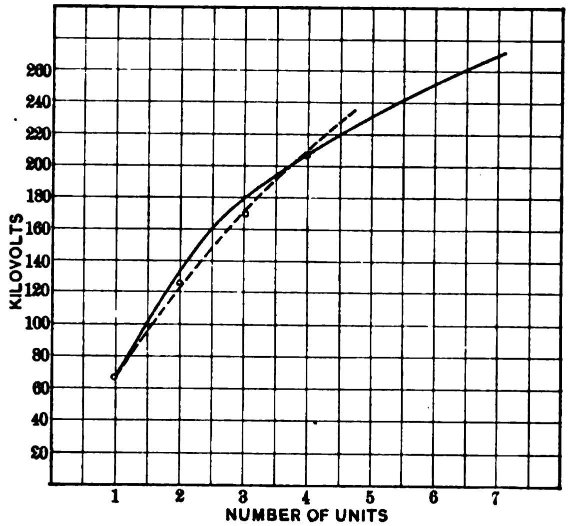


FIG. 10—CALCULATED FLASH-OVER VOLTAGE
0 = Test points

The capacity of the various units against ground may be inserted in the equations and evaluated by taking readings with successive points of the transformer winding grounded, thus giving P_0 definite arbitrary values.

If the capacity to ground were appreciable in comparison with C_1, C_2, etc., the flash-over voltage would vary with the value of P_0.

Flash-over tests were made under these conditions but no appreciable difference could be detected from the results obtained with the neutral grounded; for this reason the capacity to ground has been neglected. Its general effect, if present, would be to make the potential distribution asymmetrical, throwing more stress on the units next to the line and less on those next to the tower.

For high-frequency surges the potential distribution is indicated more correctly by the calculated curve of Fig. 10 than by the test results, for, because of the time-lag of corona formation, auto-grading is absent.

The effect of increased conductance by deposition of moisture on the surface is to even out the potential distribution over the various units, and it is even possible that where the failure is by successive discharge the insulator will flash over at a higher voltage wet than dry.

These results show that in order to improve the characteristics of suspension type insulators the capacity should be graded to have the larger units near the line and tower and the smaller at the center of the string, to even out the symmetrical unbalancing, and with perhaps the line unit slightly the larger, to take care of the effect of any ground capacities which may be present.

The experimental work of this investigation was carried out at the high-voltage laboratory of McGill University in conjunction with Mr. O. F. Hague and under the direction of Dr. L. A. Herdt.

Harris J. Ryan (by letter): Some tests were made in March, 1912, for the Bureau of Los Angeles Aqueduct Power, to determine the manner in which capacity to neighboring unit, capacity to ground, capacity to the line conductor, corona, water vapor and rain conduction, damp dusty surface conduction, etc., affect the voltage duty of the individual unit, or the "grading," as it is called in the present paper. Table I shows unit voltage duties obtained in these tests for the dry six-unit suspension insulators:

TABLE I

Number of units	Kilovolts across unit	Kilovolts across unit	Kilovolts across unit
1	10.3	12	18.4
2	12	14.1	21.7
3	11.9	13.9	15
4	7.2	8.4	21.6
5	6.3	7.3	11.7
6	6.3	7.3	11.6
Total	54	63	100

Other data:

e_1 = flash-over in kilovolts per single unit = 76; altitude at which test was made, 3900 ft. (1189 m.) above sea level; e_1 at sea level given by manufacturer, 90.

c_2/c_1 = ratio of mutual to ground capacities, not measured, supposed to be about 25.

[MC NAUGHTON]

FIG. 13

[MC NAUGHTON]

FIG. 12

[MC NAUGHTON]

FIG. 11

Ordinary temperature and barometric values existed during the tests.

Top unit grounded as on tower.

Bottom unit three ft. (91 cm.) from ground supporting No. 0000, B. & S., line cable.

These six-unit insulators may be considered as having a normal voltage to ground rating of 54 kilovolts.

In complete darkness no trace of visible corona appeared over any part of the insulator under the application of less than 100 kilovolts.

The frequency used in the tests was 60.

Corona appeared on the No. 0000 line conductor at 63.0 kilovolts. It must be remembered that this was a single-phase circuit in which the line conductor was held three ft. (91 cm.) above the ground. The importance of the capacities of the units to the line conductor as a factor controlling the voltage duties of the individual units was brought out by the fact that the unit next to the line conductor did not in any of the tests sustain the highest voltage duty; such highest drop in voltage occurred usually across the second unit above the line conductor, though sometimes the third or even the fourth unit was subjected to about the same duty as the second.

TABLE II

	Kilovolts across each unit		
Number of units	Theoretical (Peek)	Aqueduct Power	
		54 kv.	100 kv.
1	100	80.3	77.5
2	83	93.5	91.1
3	71	92.7	63
4	62	56.3	91
5	57	49.1	49.2
6	48	49.1	49.2
Total	421	421	421
Eff. per cent	70.2	75	77

The effect of conduction in the atmosphere produced by corona on the line conductor is brought out by the change in the insulator efficiency taken in the same manner as described in Mr. Peek's paper. Thus at 54 kv. the efficiency is 74.5 per cent; at 63 kv., just at the corona start, the efficiency is unchanged, and at 100 kv. it has increased to 77 per cent. The efficiency would continue to increase slowly as the voltage is raised until the insulator failed through a cascading flash-over. At the efficiency of 77 per cent the insulator would fail at 6×76 ×0.77 = 350 kilovolts. It is a fact, as just noted, that the increased corona at flash-over would increase the efficiency by a small amount and therefore this value of 350 kv. would be slightly increased correspondingly.

The $e_1 = 74$ and $c_2/c_1 = 20$ insulator of Fig. 19 in the paper is almost identical in characteristic make-up with the insulator employed in the Aqueduct Power tests. The curve in the figure shows that the suspension insulator in Mr. Peek's test flashed over for six units at 325 kv., which is in fair agreement with the above value of 350 kv., considering the differences in c_2/c_1.

In Table II the *theoretical* values are taken from the interpolated curve, $e_1 = 100$, $c_2/c_1 = 20$, $n = 6$, of Fig. 14, for the voltage duty of individual units as computed by Mr. Peek, using his theoretical method. The *Aqueduct Power* values are those given in Table I at 54 and 100 kilovolts, scaled to the same total voltage used by Mr. Peek, to facilitate comparison.

In comparing these values it is also well to remember that the Aqueduct Power insulator had a higher value of mutual to ground capacity ratio than the insulator used in Mr. Peek's tests.

The results of our dry insulator tests show that while the voltages across the individual units are quite different from the theoretical values obtained by Mr. Peek, such differences are largely *compensating*, so that substantially the same over-all actual efficiencies are obtained.

Experience has shown that the unit next to the line conductor is the one in a set most apt to puncture. It is not the one subjected to the highest operating voltage. Normal puncture voltage is made to exceed flash-over voltage by 20 to 50 per cent, dependent upon design and altitude. These facts indicate that the puncture is due to the application at the insulator of voltage higher than the flash-over value, so suddenly that puncture takes place before corona has time to develop sufficiently to concentrate into a flash-over. This accords with the possibilities made evident by experimental physics and with the views expressed in the paper.

In Mr. Peek's present paper all known factors that unite to bring about the failure of a suspension insulator are analyzed and the results of many tests are given. These analyses and tests have demonstrated unmistakably that over a wide range of types and operating conditions the single-unit flash-over voltage, e_1, and the mutual-to-ground capacities ratio, c_2/c_1, are truly the "bench marks" of the characteristic topography of the suspension insulator.

Practically, in any given endeavor, the contributing factors are varied and numerous. A few factors, however, are generally responsible for the characteristic results produced, and the rest work for and against such results—they do not in the aggregate have much effect. At best a theory can correlate and apply only a few factors. A useful theory must rest upon a thorough knowledge of all factors, those that have been excluded as well as those that have been included. The present paper is of much value, therefore, because of the success with which the theoretical factors have been separated from the total mass of factors that bring about the aggregate behavior of the suspension insulator.

R. P. Jackson: In regard to the compression chamber lightning arrester, my experience has been that when non-arcing gaps are enclosed in a chamber of any kind, or when gaps, in fact, are enclosed in a chamber where rapid discharges take place, the metal fumes tend to make a continuous arc. It is well known that in unit switches, or any place where fumes of metal go out into the insulating spaces, these fumes will cause the arc to jump long distances, so, while not questioning the results obtained in the experiment, I am somewhat surprised at the effort to produce an arrester using a gap in an enclosing chamber, where the fumes cannot escape.

In regard to the protection of the single-phase railway motors, the single-phase system generally has sustained no injury from lightning, and practically nothing has been necessary in the way of protection of the motor, because the motors are on the low-tension side of an auto-transformer. The auto-transformer very seldom suffers, as it is rugged and strong and well insulated.

High-voltage direct current is not subject to any such automatic or natural protection. The motors are at least as vulnerable as the old 500-volt direct-current, and the higher voltage and the higher insulation of the line, and the greater number of turns in the armature, undoubtedly make the high-voltage direct-current system weak in this respect.

That is a direction in which experiments must be carried out, and in which the results given in the paper indicate good work has been done, and will have to be continued, to make high-voltage direct current as reliable as the old 500-volt direct current, because it is the one weak spot in that system.

It may be said that the experience with the ordinary railway motor is that the new motors do not suffer from lightning. The trouble is not with the new equipment, but with re-wound motors, motors which have been in service, which have had their armature cores bruised and new coils put in. The new coils which are put in may not be as strong as the original ones, and there is where the difficulty appears. This will also be true of the high-voltage direct-current motors coming into use.

The direct-current electrolytic arrester is the most effective arrester for protecting motors, generators and anything of that kind. I should like to know if it has been found that operating men in general will give the necessary care to such a sensitive and fragile device—they are more or less sensitive and require some care and attention. Psychologically, the condition is the same as when a man is cured of a trouble—he neglects the remedy, and the trouble recurs. The use of such a sensitive protective device would apparently be subject to the same psychological condition.

The insulator question is of great interest. I notice the fact that wet insulators have a higher flash-over voltage than the same insulators dry. It is a curious fact that while lightning is supposed to occur, usually, during thunder storms, it does not always so occur, and storms which are attended with lightning, both on the line and the power equipment, are most serious just before the rain begins to come down, when everything is dry. The insulators are more readily damaged, the lightning goes into the power house, and generally the dry line brings about lightning troubles which are a good deal worse than those coming after the insulators are all wet.

There is no mention of the fact that the insulators on the line, when all wet and leaking slightly, make good lightning arresters; and suddenly the lightning trouble vanishes because the rain has come down and made each insulator a mild lightning arrester. It would seem to me that an insulator which was designed so that its action would be about the same, either wet or dry, would be an excellent design; that is, it would not be likely to fail or suffer when it was wet, and would be equally good dry.

I was somewhat surprised to learn that there is a difference in the quality of the water. It is mentioned in the paper that highly conducting water, or non-conducting or high-resistance water, makes a marked difference in the insulator voltage flash-over. How is it with rain? Is rain, being a distilled water, a highly resisting water, or can it be considered, as in Pittsburgh, for example, a pretty good conducting water?

Charles P. Steinmetz: These papers are so complete that I have practically nothing to add, but want to draw your attention to a very interesting phenomenon which is contained in the subject matter of two of these papers, that on the compression chamber lightning arrester, and the one on the suspension insulator. What I refer to is the potential distribution in a circuit containing distributed capacity in two different forms, as distributed series capacity and as distributed shunted capacity. In the compression chamber lightning arrester we have the capacity between adjacent disks and also the capacity of each disk to ground, the former a series, the latter a shunt capacity. In the string insulator we have the capacity across each insulator and the capacity from the connection between adjoining insulators to ground. In such a system the potential distribution is not uniform, but the potential is higher at some places than at others. You will see that the problem dealt with in one of the two papers is just the reverse of the other one. In the suspension insulator the problem is to get as uniform potential distribution as possible. In the compression chamber lightning arrester the problem is to get as ununiform potential distribution as possible, that is, to concentrate as much potential as possible across the first condenser.

This is obvious, because in the suspension insulator the purpose is to hold back as high a voltage as possible with a minimum number of condensers. In the compression chamber lightning arrester the object is to be able to use as many condensers in series as possible with the same breakdown voltage, so as to get the arc-rupturing effect of as many gaps in series as you can get. So you see there is the same phenomenon applied in two opposite directions.

The phenomenon was recognized first in the early days of the multi-gap lightning arrester, when the attempt was made to develop it for very high voltages and, as we know, that attempt failed, due to this phenomenon. It was not possible to design multi-gap lightning arresters for 60,000 volts and over within any reasonable size, due to the phenomenon of unequal potential distribution by the combination of shunt and series capacity.

There is one interesting conclusion or suggestion which may be drawn from a consideration of the string insulator. We have seen that as nearly uniform potential should be secured as possible, to get higher break-down, and also the equations given in the paper show that the potential distribution between the insulators is independent of the frequency, that with two capacities acting in combination, each capacity takes a current proportioned to the frequency, so that in the relative currents and the relative distribution of potential, the frequency does not come in, apparently. However, in reality, when you come to very high frequencies, the frequency does seem to come in, because experience shows that in a transmission line very high frequencies, like oscillating discharges, lightning discharges, etc., act differently in their disruptive effect from low frequency. At the relatively low test frequency such an insulator string flashes over the whole string without puncturing. We find that very high frequencies, such as lightning, have the effect of puncturing the insulator nearest to the line, showing that the distribution at these extremely high frequencies is more ununiform.

An explanation of this may be the equalizing effect of the brush or corona discharge, which changes or increases the capacity of the insulator near the line, where the voltage is higher, and so evens out the potential distribution. Then the conclusion which we would have to draw, at least the suggestion which presents itself, is that at very high frequency brush discharge or corona does not act to equalize the potential distribution. That means that the brush discharge does not appear, or in other words, it seems to point to the conclusion which other phenomena also have made probable, that corona or brush discharge is not an instantaneous phenomenon, but is a phenomenon which requires some appreciable time to develop—that when you apply a very high voltage the corona does not instantly rush out from the conductor, but gradually builds up the stresses from the insulator, and therefore, if the voltage is instantly applied at very high frequency, there is no brush discharge or corona, or at least a very small corona, while at low frequencies the corona exists.

I think this is a suggestion which is worthy of further investigation, because naturally brush discharge and corona at high voltages is an important factor, which determines potential distribution, and if it should not exist at some frequencies while existing at other frequencies, then we would not be able to judge of the potential distribution at high frequencies from that at low frequencies, and we would not be able to judge of the disruptive strength of the apparatus and its reliability at high frequency from that at low frequency.

Charles F. Scott: These papers seem to me, as a group, to be an admirable presentation of a combination of theory and mathematics, of simple things, of manufacture, of engineering design, of operating conditions, and of looking forward to the future to the new and larger work which is to come. It is a remarkable group of papers.

A striking feature of these papers is that they present simple things. I can scarcely recall a new principle involved in these papers, but there are new ways of doing things, combinations of simple things in condensed form, and fundamental elements of electrical engineering and of mechanical engineering are utilized in a way to meet new problems in new ways.

Some of the papers, notably those on lightning arresters, will be recognized by some of the older of us as another step in the progress which has been going on for twenty years. This old so-called non-arcing lightning arrester had its beginning some twenty years ago, and has evolved one step, and then another, and then another, and is now attaining a very simple and obvious form by which to accomplish the results which have been aimed at all these years.

I think that, as representing the Institute at large, we ought to commend the excellent work which is being done here by this corps of engineers of the manufacturing company, and the policy of that company in doing this kind of pioneer work. It is not in a narrow sense—merely making and selling machines, but it is doing that large kind of engineering work that is needed for the transmission interests of the country and for that larger electrical progress in which we are all concerned. So that I am sure that what I may say in commending the good constructive work which is now being done here will be acquiesced in by the Institute members from abroad, and we all join in a hearty expression of our appreciation of its presentation before us.

R. Philip Clark: A question has been raised as to the maintenance and care of the direct-current aluminum arrester. At the time this arrester was first placed in commercial operation, several years ago, the principles involved were quite new and the operating characteristics were so radically different from those of any other arrester, that it was only rarely that the aluminum arrester received proper attention. As a result of these and other conditions the arresters often failed to have a satisfactory life.

The arrester has been improved since its first appearance, both in design and in the materials used. The addition of the balancing resistance has overcome the unbalancing of potential across the cells and has thus eliminated one of the most undesirable characteristics of the arrester. Subsequent improvements in electrolyte and aluminum plates have made possible a much longer life than was obtained with the first arresters. However, when direct-connected to the line this arrester has only a moderate life as compared with the gap-resistance type of arresters. In view of this, the use of the direct-connected direct-current aluminum arrester is at the present time generally restricted to installations where the service is very important or the lightning conditions very severe. Periodic inspection of the arresters is essential, and the frequency varies from once a week to once a month, or at even greater intervals, depending upon the local operating conditions. Renewals of electrolyte and plates are likewise governed by the conditions of service, but generally average once every two years.

Another type of direct-current aluminum arrester has been developed for car service which is much more satisfactory from the standpoint of maintenance and care. This arrester, which is provided with a series vacuum gap, has a protective value which is only slightly inferior to the direct-connected aluminum arrester. The motion of the car causes the arrester to be automatically charged by means of a special charging gap. A suitable resistance is placed in series with the charging gap to prevent a destructive charging current whenever the arrester has been out of service for any length of time.

It is expected that this latter type of arrester will have a useful life of three to four times that of the direct-connected aluminum arrester. In addition to this, the gap type of aluminum arrester is much better adapted to street car service, as it requires no special precautions when a car is replaced in service after a period of idleness.

Cassius M. Davis: Since the paper by Mr. Cunningham and myself was written, an effort has been made to account for the rather large discrepancy in the values of the length of the line as determined from the measured inductance and capacity and as determined from the oscillograms.

The first check made was the actual measurement of the natural period of the line. For this purpose the line was connected to a small high-frequency generator. Oscillograms were taken of the charging current of the line, at various frequencies above and below the resonance frequency. Each oscillogram also showed a 60-cycle timing wave. A constant potential of 120 volts was impressed upon the line by the generator and the charging current was read on an ammeter in series. The curve plotted between frequency and charging current shows resonance at 353 cycles. This figure corresponds very closely to 363 cycles as calculated from the measured values of inductance and capacity.

The second check comes as a result of the measurement of the speed of propagation from oscillograms which record only the currents of the impulses.

It was suspected that the current taken by the oscillograph vibrators which were used to indicate the voltage of the impulses might act as a serious leakage conductance, and, if this were so, oscillograms which showed no voltage curves would give a more nearly correct value of the time of propagation from which the length of the line could be determined. This was found to be the case, and the average length of line comes out to be in one case 126 miles (203 km.) and in another 132 miles (212 km.), the average of which, it will be seen, is almost exactly the same as calculated from the measured line constants, 128 miles (206 km.).

T. A. Worcester: I wish to express my appreciation of the remarks made by Messrs. Lincoln and McClelland in connection with the ground wire assisting in the support of transmission towers. I agree entirely with their opinion. As to Mr. Lincoln's remarks regarding the stretching of conductors, I think it is dangerous to allow the conductor to stretch. The stretching of the conductor, while mounted on the transmission line, will not be the same as when it is being drawn in manufacture. Stretching of the transmission wire will probably occur at the cable clamp or tie wire, or at some weak place in the span, and the section of the conductor at that place will be reduced so that a future break will undoubtedly occur there.

In connection with the remarks of Mr. McClelland on the suspension type of insulator, I do not believe it would be desirable to allow very much for the extra length thrown in the conductor when the wire breaks, by the length of the suspension insulator itself. The length of the insulator is not added to the conductor until the wire actually breaks, and then it is useless. Further, when the wire does break, and the insulator is drawn up to a horizontal, instead of vertical, position, there is a very severe jerk on the tower, likely to wrench the cross-arms and loosen them.

F. W. Peek, Jr.: I want to elaborate a little on the point that Mr. Lincoln has brought out in regard to increasing the capacity of the line unit. Decreasing the thickness of the porcelain between pin and cap on the units of a string, by increasing the mutual capacity without changing the capacity to ground, may often actually increase the arc-over voltage of the string. For high string efficiency the problem is to make c_2/c_1 as high as possible. There is also a best ratio between pin diameter and cap diameter for minimum stress on the porcelain next to the pin—that is, for a given internal diameter of cap the puncture voltage may often be increased by increasing the diameter of the pin and thereby decreasing the thickness of the porcelain. With regard to the effect of rain in improving voltage distribution, the leakage current through the water is generally very large compared to the capacity current, and therefore predominates in the balancing effect.

In the equations the effect of the line conductor, as being slightly greater on the unit nearest the line, is not considered. This would complicate matters to a great extent without adding in any way to the value of the equations. The effect is to lower slightly the voltage on the first unit. The actual string voltage and efficiency are not, however, appreciably changed from values calculated from the equations. I have read Professor Ryan's discussion with great interest. Taking the data given for the Aqueduct Power insulator,

$$e_1 = 76, \quad \frac{C_1}{C_2} = 25, \quad n = 6,$$

from Table X in *Electrical Characteristics of the Suspension Insulator*, we find by interpolation $k = 6.5$. Then from equation (4*a*),

$$E_a = \frac{e_1 x}{k - 1} = \frac{76 \times 25}{6.5 - 1} = 345$$

This checks fairly well with Professor Ryan's result. It would have been interesting if Professor Ryan had indicated the method by which the voltages across individual units were measured. In making this measurement it is difficult to find a means whereby the voltage balance will not be changed by the measuring instrument. We have made a number of such measurements, the values of which check fairly well with the theoretical ones, but we have never been quite sure that the voltage distribution was not changed by the measuring instrument.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

FREQUENCY

BY D. B. RUSHMORE

The subject of frequency for commercial power and lighting systems, far from being settled, is discussed again with every new installation. Frequency affects the operating characteristics of circuits and apparatus, and also their cost.

The frequencies in commercial use in this country are shown in the upper part of the accompanying table. While 40 cycles might possibly have been the best frequency for general use, it did not become standard, and the choice is now between 25 and 60 cycles. The uncertainties regarding future developments in large railway work have to be given some consideration. The physiological effect of different frequencies has been shown to be a matter of much importance and it is being investigated. Of the effect of different frequencies of light rays on vegetable life but little is yet known.

In the following discussion the influence of frequency will be treated in connection with generators, transformers, transmission lines, lightning, induction motors, synchronous motors, frequency changers, synchronous converters, railroad work, switching phenomena and illumination.

GENERATORS

A general formula for the induced e.m.f. of all generators is as follows:

$$E_1 = 4\, k_w\, k_f\, f\, n\, \phi\, 10^{-8}$$

The frequency of synchronous machines in alternations per minute is equal to the number of poles times the revolutions per

FREQUENCY

	Cycles	Wave length
Alternating-current field	15	20,000 km. = 12,500 mi.
	25	12,000 km. = 7,500 mi.
	30	10,000 km. = 6,200 mi.
	33	9,100 km. = 5,650 mi.
	40	7,500 km. = 4,650 mi
	50	6,000 km. = 3,750 mi.
	60	5,000 km. = 3,100 mi.
	66	4,550 km. = 2,800 mi.
	125	2,400 km. = 1,500 mi.
	133	2,250 km. = 1,400 mi.
Sound—Lowest audible	15	66 ft. in air
Highest audible	8,000	1.5 in. in air
High-frequency currents, surges, oscillations, arcing grounds, lightning, etc.		
Wireless telegraph waves	10^5 10^7	3 km. = 10,000 ft. 30 m. = 100 ft.
Hertzian waves	10^7 10^9	30 m. = 100 ft. 30 cm. = 1 ft.
Limit of electric waves	5×10^{10}	0.6 cm. = 0.25 in.
Visible light rays:		
Ultra-red	3.7×10^{14}	81×10^{-6} cm.
Red	4.61×10^{14}	65×10^{-6} cm.
Orange	5.15×10^{14}	58.3×10^{-6} cm.
Yellow	5.44×10^{14}	55.1×10^{-6} cm.
Green	5.86×10^{14}	51.2×10^{-6} cm.
Blue	6.32×10^{14}	47.5×10^{-6} cm.
Indigo	6.66×10^{14}	44.9×10^{-6} cm.
Violet	7.5×10^{14}	40×10^{-6} cm.
Ultra-violet rays	7.7×10^{14} 30×10^{14}	39×10^{-6} cm. 10×10^{-6} cm.
X-rays (estimated)	3×10^{18}	0.1×10^{-6} cm.

minute, and the periodicity or cycles per second is shown by the following equation:

$$\text{Cycles} = \frac{\text{number of poles} \times \text{rev. per min.}}{120}$$

The following tables show the speeds for 25 and 60 cycles for which generators are usually built:

60 Cycles			25 Cycles		
3600	1800	1200	1500	750	500
900	720	600	375	300	250
514	450	400	214	187	167
225	200	180	150	125	107
164	150	120	100	94	83
100	90	80	62	58	
72					

Parallel operation is more satisfactory at low frequencies, so far as the variation in angular velocity is concerned. Due to other factors, the conditions for parallel operation depend more upon the relations between natural and impressed frequencies, rather than upon the absolute value of either.

When two synchronous machines are operated together on the same system there is a natural frequency of oscillation between them. This is represented by the following formula:

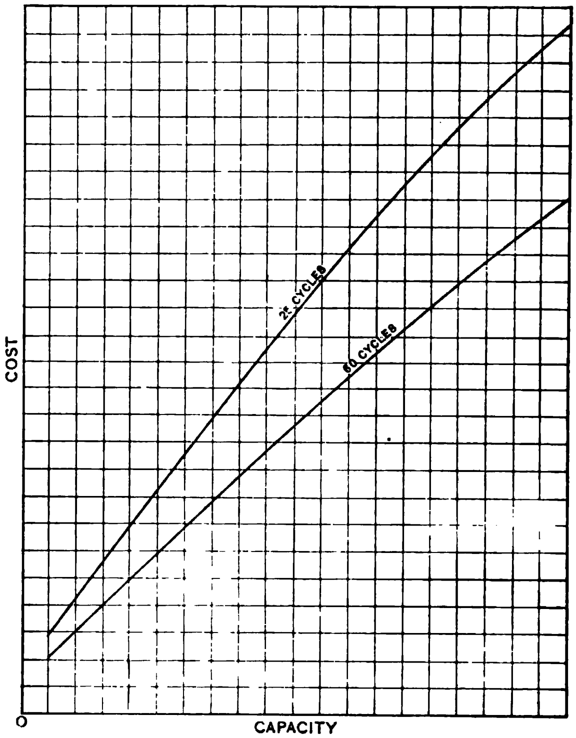
$$P_n = \frac{35{,}000}{\text{rev. per min.}} \sqrt{\frac{f \times kw. \times S_1}{WR_1^2}}$$

With reciprocating apparatus a frequency is impressed on the system by the relation of the impulses of the engine, and if this frequency approaches the natural period, trouble from hunting is likely to occur.

Due to the lower core loss with lower frequencies, the efficiency is naturally better at 25 than at 60 cycles. The cost is also increased by the frequency, as shown in the curves, there being a natural tendency for 25-cycle apparatus to be heavier than 60-cycle.

Due to the fact that there is a natural relation between the windings of electrical apparatus which varies inversely as the square of the frequency, the higher the frequency the greater, in general, is the peripheral velocity at the same revolutions per minute. Increase in peripheral velocity means a larger diameter with a smaller length and a better natural ventilation.

As a general rule, the labor item is higher on the higher frequency machines, and the material item higher with the lower frequencies.



SYNCHRONOUS GENERATORS.

TRANSFORMERS

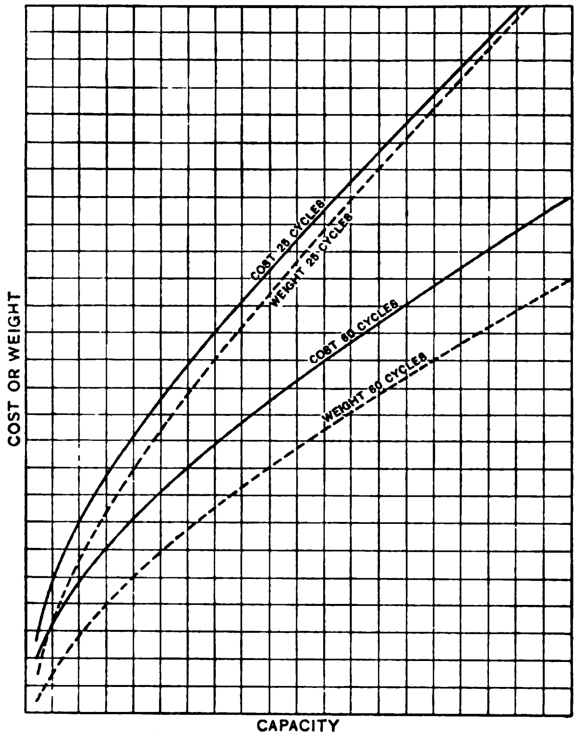
The fundamental equation for the induced e.m.f. being as follows:

$$E_1 = 4.44 f n \phi 10^8$$

it is easily seen that the influence of frequency on the design and operation of transformers is of first importance. With transformers and other electric apparatus using two windings and an iron core, the ratio of turns, other factors remaining the same, will be approximately inversely as the square root of the frequency. The lower the frequency the larger the flux, and the larger the number of turns for the same voltage. Therefore, transformers increase in cost and weight as the frequency decreases, as shown in the curves.

The regulation of 25-cycle transformers is not quite as good as for 60-cycle on account of the increased drop, due to the greater number of turns and their increased mean length.

The output of a transformer is a function of the magnetic and current densities at which the iron and copper are working, the space factor, the area of the iron and copper sections, and the frequency at which the transformer is working. With other things constant, the greater the densities at which the iron and copper are working, the greater will be the output of the transformer, while on the other hand the iron and copper losses will also be greater. The limit to which the densities may be increased is set for the core by the point of saturation of the iron, and in the copper by the consideration of heating.



WATER-COOLED TRANSFORMERS.

The output as related to the frequency, with other things equal, is such that approximately

$$Kv\text{-}a. \propto f^{0.41}$$

TRANSMISSION LINES

All insulating material is supposed to be affected by dielectric hysteresis, which varies directly as the frequency. The equation for dielectric hysteresis is as follows:

$$P_d = 2 \tan \theta f C E^2$$

This has not, up to the present time, been regarded as an important factor in the breakdown of insulating materials.

Transmission lines are designed from considerations of regulation and efficiency. The regulation is better as the frequency is lower, and so for commercial work 25 cycles is preferable to 60 cycles, considering the line alone. The capacity current plays an important part with small units and high voltages, rendering it often impossible to throw one machine on the line alone. Both the reactance and the capacity current of the line are proportionate to the frequency, as shown by the following equations:

$$\text{Reactance} = 2\,\pi\, f\, L$$
$$\text{Capacity current} = 2\,\pi\, f\, C\, E$$

The continued extension of voltage and length of lines will undoubtedly necessitate the use of shunt reactances across the phases to neutralize the charging current by the wattless magnetizing current, but the best result would be obtained by having the reactance automatically cut out as the load comes on the receiver circuit and increases the magnetizing current of the transmission system. For practical purposes, however, a mean value of reactance would probably be designed which would give the best results throughout the range of load under which the system is operated. The use of synchronous apparatus along the line and at the receiving end, can, of course, be made to play the same purpose as either capacity or reactance, by either over- or under-exciting the machines.

In long transmission lines at the higher frequencies, with an inductive load in the receiving system, trouble is not infrequently experienced from the sudden removal of the load, due to the excessive rise of voltage which limits the sensitiveness with which the lightning arresters may be adjusted, and other disturbances may also be encountered.

Many phenomena connected with the operation of transmission lines bring about electrical disturbances. The frequency of these is entirely independent of that impressed on the system. Certain quantities of electricity may be set free on the conductor, due to the discharge of lightning. After the removal of the impressing influence these oscillate with the natural frequency of the line, which is given by the following equation:

$$f_1 = \frac{7900}{\sqrt{L_m\, C_m}}$$

It is desirable to keep the natural frequency of the system as far as possible from the operating frequency, or from a multiple of it. The apparatus connected to the line usually differs from the natural frequency to an extent which is difficult of determination.

One of the limiting features of increasing the voltage on transmission work will be the loss by corona. This is proportionate to the frequency, and may be calculated from the following formula:

$$P_c = \frac{k_1}{\delta} f \sqrt{\frac{r}{S}}\,(e - e_0)^2 \times 10^{-5}$$

It has been proposed to utilize corona loss as a protective measure by making the wires of the line near the power house and substations just below the normal size, so that any considerable increase in voltage would bring about its proportionate corona loss. Up to the present the determinations of corona loss as regards its correction by transient voltages and magnitude of loss at the voltages which would occur, do not seem to give great promise of this as more than a slight assistance for protection. There is no reason, however, why this should not be used for what it is worth, and that many times it would be of some unknown value as a protective device.

Due to the voltage rise which takes place on long high-current lines, even from the charging current, and especially where the lines are placed at different altitudes, one part of a system may be giving a considerable corona loss while another section of the line is, both in factors of voltage and altitude, below the critical point.

The resistance of wires and cables carrying alternating currents is also affected by the frequency, in that the current is not distributed uniformly over the cross-section of the conductors, the current density being higher near the periphery. This is known as " skin effect ", and results in an increased resistance. The effect is, however, negligible for low frequencies and small conductors, but increases rapidly for higher frequencies and large conductors. With magnetic material it is much higher than with non-magnetic. The equation for the skin effect coefficient is given by the following approximate formula:

$$C_s = \frac{1 + \sqrt{1 + \left(\frac{k}{\delta}\right)^2}}{2}$$

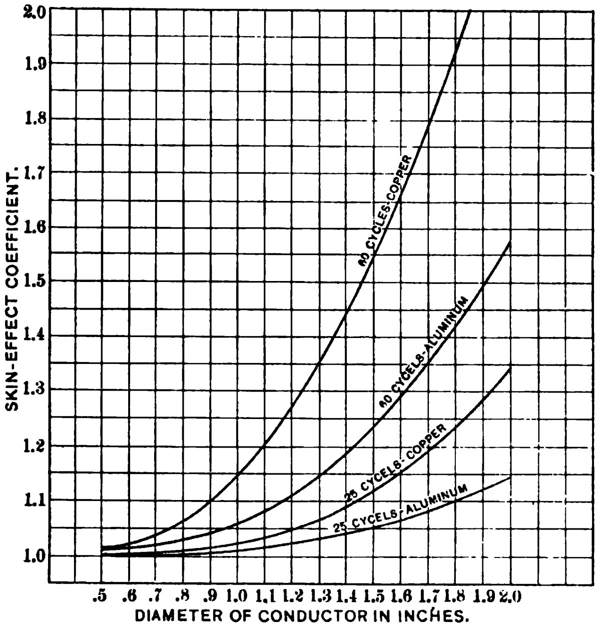
For copper $\left(\frac{k}{\delta}\right) = 0.0105\, d^2 f$

For aluminum $\left(\frac{k}{\delta}\right) = 0.0063\, d^2 f$

The values of the skin effect coefficient for copper and aluminum are given in the following curves, both for 25 and 60 cyles. For the true resistance, multiply the ohmic resistance by the skin effect coefficient.

For certain kinds of transmission work and especially for long spans, duplex metals are being used, where a steel core is surrounded by a copper or aluminum cylinder, or a stranded cable wound on the steel core. The object of this, of course, is to gain additional strength from the steel while possessing the conductivity of the copper or aluminum. Such a construction could, however, be well used where any question of skin effect is presented.

The constants of an electric circuit are found in the mechanical analogues of systems possessing inertia and elasticity where the movement resulting from either is retarded by resistance. In the case of a material possessing elasticity and inertia and being disturbed by stress, the return to a condition of equilibrium is accompanied by oscillations or not, depending upon the constants of the system. This is true of the discharge of a condenser or capacity charge in an electric circuit, and is developed by the relations of the resistance, reactance and capacity. If R^2 is equal to $\frac{4L}{C}$ the discharge takes place without oscillations, but just bordering on that condition. If we have the condition R^2 less than $\frac{4L}{C}$ the charge oscillates until the energy is discharged in the resistance. Where R^2 is greater than $\frac{4L}{C}$ no oscillation takes place and no abnormal voltage is produced in the circuit. It should be recalled that the rise of voltage always takes place across the reactance. This is a specific case of a very general law.



SKIN EFFECT

LIGHTNING

The protection against high-potential phenomena produced in electric circuits by atmospheric lightning is of the greatest importance in transmission systems.

Any equalization of the potential distribution in a thunder cloud above a line by a lightning flash will cause a change in the electrostatic charge of the line, corresponding to the changed potential difference between ground and cloud above ground, and the static charge thus set free on the line will move as a traveling impulse or wave along the line. The frequency of these impulses corresponds to the frequency of the lightning discharge, some having a magnitude of about one-half million cycles. Since the velocity of propagation of electric disturbances equals the velocity of light, or 188,000 miles (302,557 km.) per second, the wave length of the impulse is $\frac{188,000}{500,000} = 3/8$ mile, or about 2000 ft. (609.6 m.).

These impulses travel along the line until their energy is dissipated, or they are reflected at the end of the line. If the latter is the case, the reflected and incoming waves may combine into a standing wave or oscillation; that is, a wave with fixed position on the line. With different oscillations superimposed upon each other, a traveling wave of moderate potential may therefore cause dangerous voltages when breaking up into oscillations, just as the rise of the ocean waves in the surf.

INDUCTION MOTORS

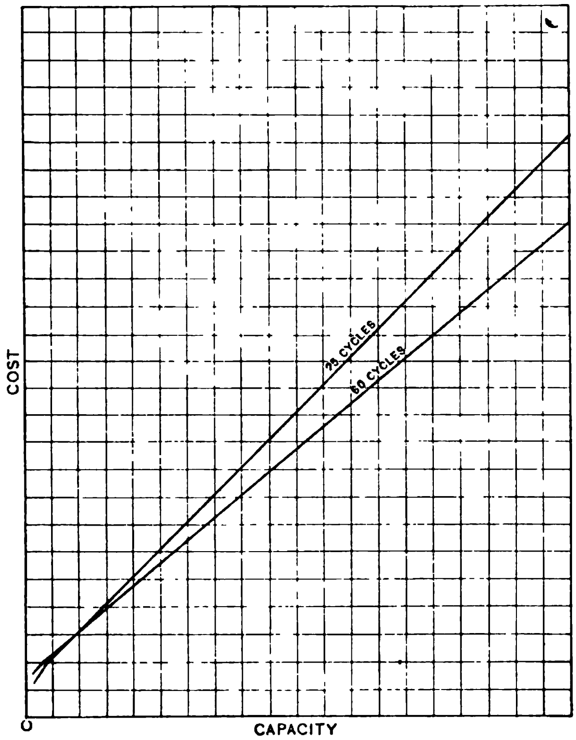
The speeds of 25-cycle induction motors for general application are practically limited to 750, 500 and 375 revolutions per minute, while the corresponding speeds for 60-cycle motors would be 1200, 900, 720, 600, 514, 450 and 400 revolutions. Twenty-five-cycle motors could, of course, be wound for two poles, giving a speed of 1500 revolutions, but this is rarely done except in the very small sizes. The objection is that since the flux per pole is twice as large as in the four-pole type, the section of iron back of the slots must be twice as great, for the same rotor diameter. Moreover, the end connections become very long and the machine difficult to wind and consequently the cost is very materially increased.

The efficiency depends upon a number of features. The lower frequency will, of course, tend to make the iron loss less, but on the other hand the copper loss will be considerably greater on account of the longer end connections, and as a rule, the efficiency is found to be somewhat lower for low than for high-frequency motors.

The power factor of an induction motor is expressed by the ratio $\frac{\text{kw. input}}{\text{kv-a. input}}$. It is affected by the reactance and the magnetizing current. At constant line voltage the latter remains practically constant, while the former varies with the current. The shape of the power factor curve, that is, the power factor at fractional loads and overloads, therefore, depends upon the relative values of the magnetizing current and the reactance.

$$\text{Power factor} = \cos \theta = \frac{R}{Z}$$

A motor with a relatively large magnetizing current and a low reactance will in general have a low power factor at fractional loads and a rapidly increasing power factor at higher loads, while a motor with a relatively low magnetizing current and a high reactance will have a high power factor at fractional loads and only a slightly greater power factor at overloads.



INDUCTION MOTORS.

The 25-cycle motor has an inherently lower reactance and requires less magnetizing current, for which reason its power factor is considerably higher than for high-frequency motors.

The starting torque and the maximum torque depend inversely on a function of the reactance, and are therefore higher for low frequencies.

The starting torque of an induction motor is equal to

$$k \frac{E^2 r_1}{Z^2}$$

The starting current is equal to

$$\frac{E}{Z}$$

The running torque is equal to

$$k \frac{E^2 s r_1}{[(r_1 + s r_2)^2 + s^2 X^2]}$$

The maximum torque is equal to

$$k \frac{E^2}{2 (r_1 + \sqrt{r_1^2 + X^2})}$$

Comparing the weights, based on motors of the same capacity and speed, it is found that, on the average, 25-cycle motors will weigh about 15 per cent more than 60-cycle motors. For the smaller sizes there is very little difference in the cost, but as the sizes increase there is a marked difference in favor of the 60-cycle motors, as shown in the curves.

SYNCHRONOUS MOTORS

The starting torque of synchronous motors is relatively small, but with the use of amortisseur windings a considerable torque is obtained at starting, particularly for lower frequencies. Any reasonable amount of torque can be provided by making the amortisseur winding of sufficiently high resistance, but the objection to this is that the higher resistance the more will the speed, up to which the rotor will be brought by the torque of this winding, fall short of synchronous speed. The ideal condition would therefore be accomplished if the starting winding could gradually be changed from one of high resistance to one of low, as the motor speeds up. This could be done by making the end rings of the armature winding of magnetic material and utilizing the " skin effect " in increasing the resistance.

At start, the currents in the end rings are naturally of the highest frequency, and consequently the skin effect and the corresponding increased resistance are also highest. As the motor speeds up the frequency of the rotor currents decreases, this in turn causing the skin effect and the increased resistance to decrease, until at synchronism the periodicity would be zero and there would be no " skin effect. " It is therefore evident that the impedance of the end rings will gradually decrease from a high to a low value as the motor gets up to speed.

When machines are driven at high speeds the choice at 25 cycles is extremely limited, and in many cases this develops a situation in which the 60 cycles is more desirable. Where, however, as is usually the case with synchronous motors, low-speed apparatus is to be driven, the machinery can usually be adjusted in speed to that of the 25-cycle motor.

The wide gap in speeds with 25 cycles operated between 750 and 1500 rev.per min., with the four- and two-pole arrangement, leaves a field which it would often be desirable to utilize were it possible to do so.

FREQUENCY CHANGERS

Frequency changers are primarily used for effecting a change in frequency. They are either utilized for obtaining a frequency high enough for lighting purposes from a low-frequency system, or as a means of interchanging power between systems operating at different frequencies.

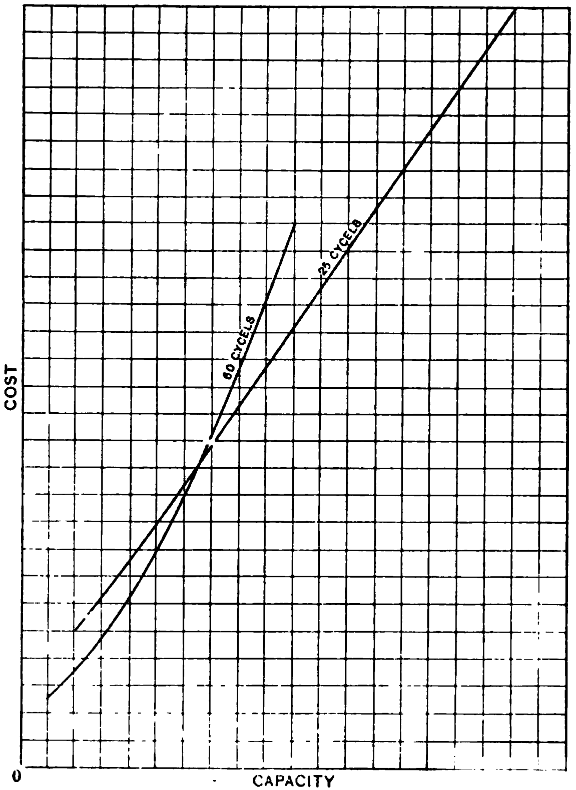
The change from 25 to 60 cycles or vice versa requires a set running at 300 rev. per min., which is a serious limitation because this speed is much too low for the economical design of frequency changers of small or moderate size. If an exact ratio is not absolutely necessary, as when power is taken from an existing system for lighting and industrial purposes, and the frequency changer is not intended for tying two generating systems together, the available range of speed is greatly increased, as shown in the following table:

FREQUENCY-CHANGER COMBINATIONS

Frequency		Poles		Speed	Generator frequency
Motor	Generator	Motor	Generator		
25	62.5	4	10	750	4.17 per cent high
25	62.5	8	20	375	4.17 per cent high
25	60	10	24	300	Exact
25	58.3	6	14	500	2.78 per cent low
25	56.3	8	18	375	6.18 per cent low
60	26.7	18	8	400	6.8 per cent high
60	25.7	14	6	514	2.8 per cent high
60	25	24	10	300	Exact
60	24	20	8	360	4 per cent low
60	24	10	4	720	4 per cent low

While synchronous motors are almost invariably used with frequency changers, induction motors may be used if proper arrangements are provided for adjusting the slip so as to insure a satisfactory parallel operation. This adjustment, of course, means the introduction of a permanent resistance and a corresponding loss, and is therefore undesirable unless other advantages of greater importance can be obtained.

Where only one set is required speed adjustment is not necessary and the motor may be designed with a slip which will just be sufficient to bring the generator frequency to the right value.



SYNCHRONOUS CONVERTERS.

Synchronous Converters

A synchronous converter being in effect a combination in one machine of a synchronous motor and a direct-current generator, the important factors in which the frequency is concerned have to do almost entirely with the continuous-current side. The continuous-current generators, as a rule, run at frequencies much below 25 cycles, and at the frequencies of synchronous converters, especially for 60 cycles and above, the problems of commutation and commutator construction become of importance.

The pole pitch on the commutator, armature or field, is the space passed through in one alternation. It is thus seen that there is a natural tendency toward higher peripheral speeds at the higher frequencies, and it is the limitation of peripheral speed which fixes the limits of design.

With direct-current machines. this occurs with turbine-driven generators and the commutators, which are necessarily mechanical in construction, consisting, as they must, of a certain amount of insulation. Direct-current generators are therefore more limited in speeds than alternating-current, and the same holds true when they are combined as in synchronous converters.

Improvements in design have made the 60-cycle synchronous converter satisfactory for the conditions under which such machines operate. At the lower frequencies, however, converters are more satisfactory in their operation, and necessarily of a greater margin of safety as regards the electrical and mechanical limits of commutation. In efficiency the 25-cycle converters are slightly higher than the 60-cycle, and the relation of costs is shown in the curves.

RAILROAD WORK

Twenty-five cycles has been recognized as the standard frequency for railway systems in this country. Until not long ago all systems were of the alternating-current-direct-current type, alternating current being generated and transmitted to the various substations, where it was changed to direct current by means of synchronous converters. The choice of this frequency was therefore chiefly caused by the less satisfactory operation of the earlier types of 60-cycle converters.

Even with the successful operation of the present 60-cycle converters, there is no reason for changing the standard 25-cycle frequency. While 60 cycles would be preferable as far as the generators and transformers are concerned, this is offset, however, by the advantages of the 25-cycle transmission system and the lower cost of synchronous converters for larger capacities. The 25-cycle lighting can also be considered as satisfactory for railway purposes.

With the introduction of the alternating-current railway motor, 60 cycles is obviously almost entirely eliminated, due to the excessive impedance drop and " skin effect " caused by the alternating current flowing in the rails. The 25-cycle system, on the other hand, is fully satisfactory for this service, and although the 15-cycle system has been advocated, its advantages over the 25-cycle system have not been proved to be of sufficient weight to necessitate a change in the present standard frequency.

In Europe, however, a few recent single-phase systems are using this frequency.

SWITCHING PHENOMENA

The interruption of high-tension electric circuits is generally accomplished by means of oil circuit breakers so as not to produce any abnormal disturbances. The rupturing capacity of an oil circuit breaker is dependent upon the velocity with which the contacts part, their size and shape, the quality of oil, the electrical characteristics of the circuit, the length and number of breaks, etc.

The most distinctive feature of the oil circuit breaker lies in the fact that when the alternating current that is maintaining the arc in the oil passes through zero, at which point the electromagnetic energy is a minimum, the current is interrupted and remains so until the voltage rises to a sufficient value to puncture the oil insulation which has been established between the contacts. As soon as this occurs, the current re-establishes itself and flows for another half cycle. This successive going out of the arc and its re-establishment thus continues until sufficient insulation is interposed between the contacts to resist the maximum voltage of the circuit. A lower frequency is, therefore, more desirable from a switching standpoint.

ILLUMINATION

Where alternating current is used for lighting, the 60-cycle frequency is generally used. No arc lamp has as yet been developed that will operate with entire satisfaction on frequencies of less than 40 cycles, and incandescent lamps cannot be used to advantage on frequencies of less than 30 cycles. Low-voltage incandescent lamps show no flicker; but the effect of fatiguing the eye is noticeable at 25 cycles, especially in high-voltage lamps.

In systems where lighting predominates a 60-cycle frequency should therefore be selected, while if most of the energy is to be used for power purposes the condition may be such that 25 cycles would prove to be preferable, in which case frequency-changers can be provided for changing the current required for lighting purposes to 60 cycles.

FREQUENCIES USED IN SOME EXISTING SYSTEMS

Central Stations:	Cycles
New York Edison Company	25 and 60
Brooklyn Edison Company	25
Boston Edison Company	60
Commonwealth Edison Company	25 and 60
Detroit Edison Company	60
Transmission Systems:	
Great Western Power Company	60
Ontario Power Company	25
Sierra & San Francisco Power Company	60
Mississippi River Power Company	25
Pennsylvania Water & Power Company	25
Southern Power Company	60
Central Georgia Power Company	60
Georgia Power Company	60
Great Northern Power Company	25
Washington Water Power Company	60
Railroads:	
New York Central Railroad	25
New York, New Haven & Hartford	25
Pennsylvania Railroad	25
Great Northern Railroad	25
Butte, Anaconda & Pacific Railroad	60
Steel Mills:	
Indiana Steel Company	25
Illinois Steel Company	25
Lackawanna Steel Company	25
Carnegie Steel Company, Ohio Works	25
Youngstown Sheet & Tube Company	25
Phillips Sheet & Tin Plate Company	60
Colorado Fuel & Iron Company	60
Mines:	
Consolidation Coal Company	60
Woodward Iron Company	25
Witherbee, Sherman & Company	25
Winona Copper Company	60
Calumet & Hecla Mining Company	25
Delaware, Lackawanna & Western Railroad Company	60
Rochester & Pittsburgh Coal & Iron	25
United States Coal & Coke Company	25
Pulp and Paper Mills:	
Kimberly-Clark Paper Mill	25
St. Regis Paper Company	60
United Boxboard & Paper Company	25
Flour Mills:	
Northwestern Consolidated Milling Company	60
George Urban Milling Company	25
Washburn Crosby Company	60

Cement Mills:

Universal Portland Cement Company, Buffington	25
Inland Portland Cement Company	60
Sandusky Portland Cement Company	25
Freeport Portland Cement Company	60
Knickerbocker Portland Cement Company	60

NOTATION

C = Capacity in farads.
C_m = Capacity in microfarads.
C_s = Skin effect coefficient.
d = Diameter of conductor in inches.
E = Applied e.m.f. in volts.
E_1 = Induced e.m.f. in volts
e = Effective applied e.m.f. in kilovolts to neutral.
e_0 = Disruptive critical voltage in effective kilovolts to neutral.
f = Frequency in cycles per second.
f_1 = Natural frequency of transmission in cycles per second.
k = Constant.
k_1 = Corona constant.
k_w = Winding factor constant.
k_f = Form factor constant.
L = Self-induction in henrys.
L_m = Self-induction in milli-henrys.
n = Number of turns.
P_c = Corona loss in kilowatts per mile.
P_d = Dielectric hysteresis loss.
P_n = Natural period in beats per minute.
R = Resistance.
R_1 = Radius of gyration in feet.
r = Radius of conductor in inches.
r_1 = Rotor resistance per phase.
r_2 = Stator resistance per phase.
S = Distance between conductors in inches.
S_1 = Ratio $\frac{\text{short-circuit current}}{\text{full-load current}}$
s = Slip.
W = Weight of revolving post in pounds.
X = Reactance.
Z = Impedance.
δ = Density factor.
ϕ = Magnetic flux.
θ = Phase angle.

The author desires to acknowledge the assistance of Mr. E. A. Lof in the preparation of this paper.

DISCUSSION ON "FREQUENCY" (RUSHMORE), SCHENECTADY, N. Y., MAY 17, 1912.

Samuel Sheldon: It is to be regretted that the author of this paper has seen fit to omit the unit costs which have been chosen for the ordinates of his curve-sheets and the unit capacities used for abscissas. Were these to be introduced, the value of the paper to the membership would be much enhanced.

John J. Frank: The comparative table of frequencies, and the table showing frequencies used in some existing systems, should command attention. Speaking as a designing engineer of transformers, in my opinion the adherence to the latter table by operating companies would greatly benefit, not only the manufacturers, but the purchasers and users of transformers as well.

Frequency shows its effect on the design and operation of transformers in several ways; the amounts of material, cost, heating, losses, exciting current and mechanical forces vary with the frequency.

It has been shown that the loss in silicon steel now generally used in transformers is about 2.7 times as great for 60 cycles as for 25 cycles at normal densities. It is obvious that a transformer for 60-cycle operation designed at the most efficient density and the corresponding watts loss per pound will not operate as a 25-cycle transformer at the same watts per pound, as the exciting current resulting from the higher density will be prohibitive. With the same flux density and the same turns, the cross-section of the core for a 25-cycle design would be 2.4 times that required for a 60-cycle design, and the relative weights of the core somewhat greater. In commercial designs no such difference in core materials would be followed, as a 25-cycle design would operate at a higher density than a 60-cycle design, and the ratio of the copper to core loss would be greater for the 25-cycle than for the 60-cycle design.

In commercial designs it is necessary, in order to reduce the cost, to have no more material than is required. A small core gives large watts per pound with correspondingly high exciting current. A large core gives increased material and a more expensive design.

By comparison of the 25-cycle and 60-cycle commercial designs we find that the efficiency of the 25-cycle designs is about 0.8 to 0.2 of 1 per cent less than the 60-cycle design, while the cost is 20 to 50 per cent greater. No absolute comparison can be made between the relative cost and efficiency, as small changes in efficiency may in the use of standard parts give large differences in cost. Frequency plays an important part in the operation of transformers. Operating a 25-cycle transformer on a 60-cycle circuit decreases the flux density and the core loss. Operating a 60-cycle transformer on a 25-cycle circuit increases the density and core loss, and in general gives a prohibitive exciting current. Frequency enters into the mechanical forces to which a transformer may be subjected, as the reactance increases with the frequency, and while the mechanical force varies directly as the square of the current, a 25-cycle transformer operating on a 60-cycle circuit would be subjected to about $\frac{1}{2}$ the mechanical strains on short-circuit. The limit of reactance in a transformer is about 8 per cent at 60 cycles and somewhat higher at 25 cycles.

B. G. Lamme: The subject of frequency seems to be a wide open one. In the beginning of this paper, attention is called to the general use of two standard frequencies. When I first started in the electrical business some 23 years ago, we had practically one frequency, namely 133 or 125 cycles per second, which we called the 16,000 or 15,000 alternation system. In those days all frequencies were given in alternations per minute, such as 16,000, and usually the frequencies were preferred in even thousands. The principal reason for the high frequency of that time was on account of the design of transformers, which were always of small capacity, for individual house lighting, and it was thought that smaller and cheaper house transformers could be built at 15,000 to 16,000 alternations than was practicable at lower frequencies.

About 1890 the question was actively taken up, of bringing into use a lower frequency, and a great deal of study was expended on the determination of a more suitable frequency. One argument in favor of a lower frequency was that it was more suitable for arc lighting, while the principal argument brought against it was that it was much less suitable for the transformers used with the incandescent lighting. In those days the induction motor was commercially unknown, and there were no synchronous converters nor synchronous motors to be considered in deciding this problem, and therefore the conditions required in arc and incandescent lighting had an almost exclusive influence in controlling the decision. It was considered that, in making such a change, it would be advisable to go to the extreme, that is, about half the then-existing frequencies, so that finally it was concluded that 8000 to 7500 alternations per minute would be as far as it would be practicable to go. A frequency of 7200 alternations per minute, or our present 60 cycles, was finally chosen, because it was the number of alternations which admitted of a nice choice of speeds for the generators. For example, with four poles, an 1800-revolution machine was obtained; six poles, 1200 revolutions; and eight poles, 900 revolutions would be obtained. These were all considered fine speeds in those days.

About 1892 the question came up, from time to time, of a still lower frequency. The first important case of this, with which I am familiar, was in connection with the first large Niagara Falls power plant. The Commission which was considering this plant was not satisfied with any of the high-frequency propositions. Professor Forbes, who was electrical engineer of the Commission, was favorable to a very low frequency, and he proposed 2000 alternations per minute, or 16⅔ cycles per second. One prominent argument which he made was that, with this low frequency, there was a probability of the use of commutating type alternating-current motors. In considering the use of a very low frequency, the company with which I am connected was favorable to 4000 alternations per minute, or 33⅓ cycles. About that time we were working on our first synchronous converters and we had built one 4-pole machine which operated at 1000 rev. per min., thus giving 4000 alternations, and we thought it was a pretty satisfactory machine, and we decided that 4000 alternations was a very suitable frequency for synchronous converters. The speed of the proposed Niagara machines of 5000 h.p. was to be 250 rev. per min. We therefore figured originally on a 16-pole machine giving 4000 alternations, while Professor Forbes figured on an 8-pole machine giving 2000 alternations per minute. Finally, as we could not get together on either of these frequencies, we compromised on a 12-pole machine giving 3000 alternations per minute, or 25 cycles per second. This was the first large installation of this sort, and I believe that this is the real origin of the present 25-cycle system. It was a pretty good compromise, but possibly, in some ways, the choice of a little higher frequency would have been better, such as 30 cycles instead of 25, in view of the fact that 60 cycles has become one of the two accepted standard frequencies. With 60 and 30 as standards, we would then have a 2 : 1 ratio of our standard frequencies, which would have some very considerable advantages, especially in frequency changing.

That these two frequencies were not generally accepted as standard, is instanced by the fact that we have had in use in this country 66, 60, 50, 40, 33, 30, and 25 cycles, and quite a number of these were brought out after the selection of the 60 and 25 cycles.

In Europe, where there had been a still greater variety of frequencies, they did not adopt any standard frequencies until somewhat later than in this country, and by that time 25 cycles had made considerable headway, so that they finally chose 50 and 25 cycles as their two standards, thus obtaining the 2 : 1 ratio. In this point they are somewhat better off than we are.

For a good many years, 25 cycles appeared to have great advantages in certain lines of work, such as in the transmission of power over long distances, and in conversion from alternating to direct current. Where synchronous converters formed a considerable proportion of the load, 25-cycle systems were used almost entirely. Therefore, almost all the large railway plants adopted 25 cycles. However, where there was but very little conversion of alternating to direct current, 60 cycles has been most generally adopted.

Where 60 cycles was adopted, and any considerable demand for direct-current service came up, this frequency proved to be at considerable of a disadvantage, from the fact that, in earlier times, motor-generators had to be used. In attempting to overcome this difficulty, the 60-cycle synchronous converter was developed, but for a number of years it was considered to be a rather poor machine, and there were, in some cases, good reasons for this reputation. The limitations of design in those days did not allow what we now consider to be a very good machine. For example, in a synchronous converter, the distance between any two adjacent neutral points on the commutator. multiplied by the alternations per minute, gives the peripheral speed of the commutator. In a 60-cycle machine, that is, 7200 alternations per minute, with 6 in., or ½ ft. (152 mm.), between neutral points on the commutator, we would obtain a peripheral speed of 3600 ft. (1097 m.) per minute, which in those early days was considered excessively high speed. It was therefore not considered practicable to make a 60-cycle synchronous converter without either using commutator speeds which were beyond the then-accepted good practise, or using distances between adjacent neutral points which were too small for good practise. Assuming we did use as little as 6 in. (152 mm.) between adjacent neutral points on the commutator, then we would have difficulty in obtaining enough commutator bars for 600 volts. With a $\frac{3}{16}$-in. (4.8-mm.) thickness of commutator bar, for example, only 32 bars could be used between adjacent neutral points, which, in general, was considered unduly small for 600-volt railway service. It is obvious, therefore, that in whichever direction we turned, we were up against practical limitations in making such machines for relatively high voltages. I remember a conversation I had with Dr. Steinmetz about 14 years ago, in which we talked about 60-cycle synchronous converters. I took the stand that 600-volt machines were not very promising, as they are limited on account of mechanical conditions. He took the stand that 125-volt, 60-cycle machines were not very promising on account of certain electrical reasons. When we got through, only the 250-volt, 60-cycle synchronous converter had any standing.

As we obtained more experience with 60-cycle synchronous converter constructions, the peripheral speed of the commutator was increased, thus obtaining slightly more space between neutral points, and we finally managed to get from 36 to 40 bars per pole, which was fairly satisfactory, but required about 4500 ft. (1372 m.) peripheral speed at the commutator. We have more recently become bolder and have raised the speed to 5000 ft. (1524 m.) or thereabout, and have thus been able to get in more commutator bars per pole. The construction of such machines is permissible, principally on account of improvements in mechanical construction. With such improvements the 60-cycle synchronous converter is taking a new hold, and it is probable that the 60-cycle field will be greatly extended on account of the greater perfection of the 60-cycle synchronous converter. In fact, 60-cycle synchronous converters are coming into quite extensive use in some fairly heavy railway propositions at the present time.

One condition which, in those early days, disturbed us very much in connection with 60-cycle synchronous converters, was that almost all of the generating plants were operated by reciprocating engines, and in some instances the generating units in the power plant would not operate satisfactorily in parallel with each other, and yet we were expected to operate synchronous converters successfully from such plants. Of course we had trouble. In those days we did not have the field-pole damper developed as it is now, although we had it in a crude form. In consequence of the bad generating conditions and the imperfect dampers, or absence of dampers, hunting of synchronous converters was not an unusual condition. Nowadays, the conditions are quite different, for we have many waterwheel and steam turbine-driven generating plants, both of which methods of drive tend to give relatively good operating conditions. To illustrate the difficulties of those earlier times, I will cite one instance where we had a 60-cycle converter operating upon a system where the generating machines would not operate satisfactorily in parallel. The synchronous converter flashed badly at times, and apparently without sufficient reason, according to the claims of the operators. We investigated the case and found that they operated the converter from either of two generating stations, which did not operate in parallel, and occasionally they would throw the synchronous converter from one generating system to the other, regardless of whether or not the frequency was exactly the same. Sometimes the machine would flash and sometimes it would not, but when it did, they complained to us about the deficiency of our synchronous converter.

For general purposes, 60 cycles has apparently proved to be the more suitable frequency. With this frequency, a less limited range of induction motor speeds is obtained than with 25 cycles. With the lower frequency, a 2-pole motor would give a synchronous speed of 1500 revolutions, but 2-pole induction motors, as a rule, do not present any particular gain in cost or weight over 4-pole machines, and therefore 750 revolutions may be considered as high speed for 25 cycles, whereas 1800 revolutions can be used about as advantageously with 60 cycles. However, when it comes to very low speed work, such as certain kinds of mill work, 60 cycles is almost prohibitive. For instance, where an induction motor is required to operate at 75 rev. per min., 60 cycles would require an 80-pole machine, which presents an almost impossible problem of design in an induction motor, if reasonable performance is to be obtained. However, with 25 cycles, such a machine may be entirely feasible.

From the preceding considerations, I think it may be safely said that the 60-cycle system is taking a new lease of life, and that a number of projects which formerly were only adapted for 25 cycles are now practicable at 60 cycles.

G. H. Stickney: In connection with the use of lamps on low-frequency circuits, much interest has been displayed with regard to the critical frequency below which flicker becomes evident or objectionable. The question has often been asked—" Is such and such a lamp satisfactory for operation on a 25-cycle circuit?" In general practise it has been assumed that 25 cycles is the minimum frequency acceptable for incandescent lamp operation. While this is approximately true, there are many factors which enter into the determination of the question under different conditions. In the first place, it is not an easy matter to define what constitutes an objectionable flicker. For the best class of lighting any perceptible flicker is, of course, objectionable. In low-intensity lighting on rough work (as in railway roundhouses) light having a very considerable flicker has been used to some extent without serious complaint.

Although the eye cannot distinguish a high-frequency flicker from steady light, the question has sometimes been raised as to whether, even under these circumstances, some eye-strain is not induced. As far as I have been able to learn, there is nothing to indicate that any such effect results. Even if a slight flicker can be observed, there appears to be no evidence of appreciable strain where the eyes are not applied constantly on close work. I have in mind a city in which the lighting circuit in the residence district was changed from 125 to 25 cycles several years ago, and apparently most of the consumers are entirely unconscious of any lack of steadiness in the light.

It is rather difficult to eliminate the influence of suggestion from the actual physical strain which would occur under a flickering light. This is evidenced by a case in which an individual used artificial light from a certain circuit daily for a period of some months without experiencing any difficulty from the light. When, however, his attention was called to the presence of the flicker, the light became immediately objectionable, causing eye-strain and headaches.

An important element entering into the perception of flicker is that of the intensity of the light: the greater the intensity the higher is the critical frequency. This flicker is often observed in the light source itself, when it is imperceptible in the illumination. In one city where arc lamps were operated just below the critical frequency, so that some objection was encountered, it was found possible to minimize the flickering effect and overcome the objection by introducing large diffusing shades, thereby reducing the intrinsic brilliancy.

Another peculiarity of flicker effect is that the peripheral portions of the retina are more sensitive to this effect than the central portion. A light operating at about the critical frequency may appear steady when the observer looks directly at it, but appear to flicker when the gaze is directed at a nearby object, so that the lamp is seen, so to speak, out of the corner of the eye. Where there are moving objects crossing the line of vision, a multiple image effect is obtained even with frequencies far above the ordinary critical value, and this is, in some cases, a deciding factor in determining whether illumination is or is not satisfactory.

With some types of alternating-current lamps the intensity of light falls nearly to zero with the current during each cycle, due to the fact that the heat is conducted away rapidly. As would be expected, the greater the amplitude of intensity variation during the cycle, the higher will be the frequency at which the flicker becomes evident. In the incandescent lamp, for example, since the filament is enclosed in a vacuum, the heat is not rapidly conducted from the filament, so the instantaneous variation in intensity is less than in any other form of lamp in general use. On the other hand, there is considerable difference in this respect between the different sizes and voltages of incandescent lamps. For example, a filament of large diameter, such as would be used in an incandescent lamp of high wattage or low voltage, would, on account of its heat capacity, be subject to a minimum variation in temperature, and therefore in intensity of light, during a single cycle. It has often been observed that such lamps are less subject to flicker than the corresponding low-wattage or high-voltage lamps.

In comparing the carbon and tungsten filaments, it should be noted that, for a given diameter of filament, the tungsten is less subject to flicker than the carbon on account of its positive temperature coefficient of resistance. In comparing lamps of equal candle power, however, both on account of its higher efficiency and the lower resistance of the material, the tungsten filament is somewhat smaller in diameter than the corresponding carbon filament and the result is that, at the ordinary frequencies, the carbon filament is slightly less susceptible to flicker.

When 25-watt, 110-volt tungsten filament lamps are operated on 25 cycles, the flicker of the bare filament is visible. It is, therefore, desirable to conceal the filament by means of a translucent shade when this lamp is operated on 25 cycles.

In this discussion the question has been treated purely from a practical standpoint. Laboratory investigations of the phenomena of flicker have been made by Dr. H. E. Ives, Dr. A. E. Kennelly and others. Report of Dr. Ives's tests will be found in the *Transactions* of the Illuminating Engineering Society for 1909, the paper entitled " Allowable Amplitudes of Frequency and Voltage Fluctuations in Incandescent Lamp Work." Reports of Dr. Kennelly's work will be found in a paper entitled " Frequencies of Flicker at which Variations in Illumination Vanish " by A. E. Kennelly and S. E. Whiting, in the *Proceedings* of the National Electric Light Association for 1907, and also a paper entitled " Flicker on Fixed and Rotating Targets," by Dr. A. E. Kennelly and others, in the *Transactions* of the Illuminating Engineering Society, March, 1911. This last paper contains references to a number of other papers on this subject.

W. J. Foster: The common use of 25 and 60 cycles in alternating-current work in this country makes it natural to discuss the question as one of comparison between these two periodicities. Inasmuch as periodicity of 50 cycles is superior to 60 for general use in building generators, I shall proceed to make the comparison between 25 and 50, and later give some points in which 50 is superior to 60 cycles in design of alternating-current generators.

In general the designer attacks his problem by deciding upon diameter at air gap. Several considerations have an influence, such as peripheral speed and length along shaft. As a rule, the diameter will be approximately the same for 25 and 50 cycles, except in generators of both small output and low speed, where a smaller diameter will be selected for the lower periodicity.

Considering the mechanical problems, the higher periodicity in definite pole machines is preferable in that the load on rim of spider is better distributed and smaller in amount at the points of attachment of poles.

Considering the electrical features, the higher periodicity is better in that less material is required, but not so good in being subject to greater eddy current losses. For generators of the same characteristics the dimensions at armature face, *i.e.*, the diameter and the length over magnet core along shaft, are the same. The slots in armature and the conductors in the slots may be made identical in the two periodicities. It is evident at once that the quantity of magnetic material in armature core for the 50-cycle generator will be only about one-half that in the 25-cycle, since the total flux per pole is just one-half and the quality of iron is now so good that the magnetic densities are limited by considerations of permeability rather than temperature. The copper in armature winding will be less for the 50-cycle because the pole pitch is only one-half, and consequently the projecting ends of winding where the coils pass around from slot to slot will be much less. The copper in the field winding will be less because the heat radiating surface is much greater, due to the fact of twice as many poles.

I have gone carefully into the design of a 5000-kv-a., 80 per cent power factor, 375 rev. per min. generator at the two periodicities—25 and 50. In accordance with what I consider the best practise, I have made the magnetic densities, both in the teeth and armature core proper and field magnet core, about 10 per cent higher in the lower periodicity. The result is as follows (comparing the 25-cycle with the 50-cycle):

Magnetic material 50 per cent greater.
Copper (armature and field combined) 30 per cent greater.
Efficiency 0.2 per cent greater.
Established current on short-circuit—the same.
Instantaneous short-circuit 30 per cent greater.
Temperature rises:
On armature and field windings—the same.
On armature core—about 20 per cent less.

The comparison at higher speeds is more unfavorable to 25 cycles. In this connection it should be pointed out that 25-cycle generators of revolving field definite pole type are impractical above 750 rev. per min., whereas the limitation for 50 cycles is not reached until 1500 rev. per min.

In justice to 25 cycles it should be stated that this frequency has the advantage in very low speeds and small capacity, such as engine-driven generators of 50 to 1000 kw. at speeds of 300 to 75 rev. per min.—as a rule both in the matter of cost and characteristics.

For generators that are of both high speed and large capacity, such as steam turbine-driven generators, there is a most decided advantage in the use of 50 cycles, as it permits of a speed of 3000 rev. per min., whereas the highest possible for 25 cycles is 1500 revolutions. As to the relative merits of the two frequencies in this class of work, practically the same conditions exist in the matter of quantity of material as in definite pole generators.

As to the advantages of 50 cycles over 60 cycles, they are such as: greater air gap clearance; greater pole pitch, permitting the selection of more slots per phase per pole in many designs; somewhat less danger of trouble from eddy currents; a speed of 3000 revolutions instead of 3600 for the highest speed, which is an advantage for most types of steam turbines.

In conclusion, I venture the statement that if all future work were to be restricted to some one periodicity, most experienced designers would vote for 50 cycles.

H. R. Summerhayes: The general tendency recently has been towards consolidation. Where a number of small plants exist, the tendency is to consolidate into a large plant, and several villages will make arrangements for a supply from one plant. Most of the small lighting plants in this country at the present time are operated on 60 cycles. As they are consolidated, the tendency is naturally to use the same frequency, and then, in larger cities, the 60-cycle is used more and more and the 25-cycle and lower frequencies are employed chiefly in the cases of special applications. A frequency of 25 cycles was selected for large systems originally, partly on account of the use of synchronous converters and partly on account of the lower capacity of the transmission line, and also because the reactance drop was less. It is now considered that a greater reactance is an advantage instead of a disadvantage. As the systems are consolidated and as the size of the systems increases, we now have systems covering whole States, and the higher reactance at 60 cycles becomes an advantage in limiting the current flowing at short-circuits. I believe, therefore, that the higher frequency will come more and more into general use, and that the lower frequencies will be used for special applications, furnished by frequency changers, and the frequency changers will also have a use as synchronous condensers for effecting good regulation on the system.

Charles F. Scott: The problem which is so admirably presented here of 25 versus 60 cycles is not one to be answered by " yes " or " no." The subject is taken up under eleven different heads, and under each one of these either frequency may be used. A large number of examples is given. In each kind of service both frequencies are used. There seems to be almost no field which cannot be occupied by either frequency, the exceptions being the single-phase railway, in which 60 cycles is not acceptable, and certain kinds of illumination, notably by arc lamps, in which 25 cycles is not acceptable. Consequently, the problem is one which must be settled for each individual case by taking into consideration the large number of elements which are here presented and determining which are the predominating and important ones. It is a question like the old controversy between direct current and alternating current in which we have indulged so largely in the past, and which, like it, is answered with two answers, instead of one.

N. J. Neall: In any criticism of 25 cycles it should not be overlooked that this frequency is now being used for commercial lighting, and with considerable success. The reason for this lies in the development of special reflectors or shades, such for example as that of the holophane type, which have been instrumental in eliminating the objectionable " flicker " which would otherwise occur.

It is of course true that 25-cycle arcs are decidedly objectionable from the illuminating standpoint; but owing to the development of the mercury rectifier, arc lighting on 25-cycle systems can in this way be satisfactorily handled.

It is at once apparent that for a large transmission proposition with a very big proportion of power load the adoption of 25 cycles throughout can be entirely justified.

J. R. Werth: It is interesting to correlate two of the ideas just presented by Mr. Lamme and Mr. Summerhayes: namely, the presence of high reactance, and, second, the advantageous use of synchronous condensers.

When voltage control by means of the latter is desired, the former is of material assistance. An analogy of this action can be seen in the case of the railway synchronous converter with reactance. We automatically secure flat-compounding or over-compounding due to two factors: the amount of reactance in the circuit, and the degree of over-excitation of the synchronous machine.

These two factors are present when a 60-cycle synchronous condenser is operated at the far end of a transmission line (which, therefore, contains an appreciable reactance) and when the field of the condenser is over-excited and controlled by means of an automatic voltage regulator.

The point I wish to emphasize is that this voltage control may be secured with greater economy on a 60-cycle circuit than on a 25-cycle circuit. The synchronous condenser is cheaper, due largely to the higher speeds permitted by the higher periodicity. Also, the higher reactance is inherent, and, therefore, an additional external reactance does not have to be installed, as has been suggested for use on 25-cycle systems by Professor E. J. Berg.

E. A. Lof: The reason why no cost figures are given is not so much from a commercial standpoint as from the fact that such figures would be worthless, as they would only represent the average for a number of machines of different speeds, voltages, etc. The curves are only intended to represent the approximate ratio of the average cost of 25-cycle and 60-cycle machines.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

OZONE: ITS PROPERTIES AND COMMERCIAL PRODUCTION

BY MILTON W. FRANKLIN

The importance of ozone as an industrial factor in certain lines of engineering is becoming appreciated quite rapidly. The relatively large number of patents which are being applied for, the increasing number of advertisements which are appearing and the character and standing of the electrical manufacturers who have entered the field, all point to a realization of Berthelot's prediction that ozone was destined to enjoy a great vogue in its application in the arts and sciences. The commercial future of ozone may be regarded as assured. The many actual applications which have already been made and the numberless fields for its logical invasion, together with recent developments of perfected ozone generators, all indicate the growing consideration which this reagent is gaining for itself.

Ozone has been known since 1785, when Van Marum noted the peculiar smell which resulted whenever a static electrical machine was operated, and while its identity was fully established by Schoenbein in 1845 and a method for its analytical determination was developed by the same investigator, it has not enjoyed any extensive application, excepting on an experimental scale, until approximately within the last ten years. This delayed recognition may be attributed to the lack, at the time, of perfected ozone generating apparatus and to the absence of commercial electricity.

The primitive ozone apparatus was designed to produce a phenomenon, the discharge of electricity through air, which, it had been noticed, was ordinarily accompanied by the production of ozone.

It was seen early that the amount of ozone produced in the naked arc, either high or low tension, was relatively small as compared with that due to the brush or "silent" discharge, and the constructional and manipulative difficulties accompanying the production of and operation of static condensers are probably responsible for the introduction of a solid dielectric interpolated between the statically charged plates of the modern ozone generator.

There does not appear to have been any very erudite opinion on the *modus operandi* of ozone generation among the early designers, and the prevalence of the type in question, viz., that with smooth electrodes and solid dielectrics, seems to be due to a desire to produce an electric field of considerable extent, in which the discharge should be uniformly distributed.

It has also been apparent for some time that at certain elevated intensities the appearance of noxious nitrogen oxides became manifest, and the objectionable circumstance was ameliorated by lessening the potential difference and increasing the interpolar spacing of the electrodes.

The scientific design of ozone generators as distinguished from the purely empirical method is of very recent inception and its beginning, naturally, is somewhat obscure. There have appeared creditable machines for the purpose, in advance of any theoretical information as to the principal involved.

PRODUCTION OF OZONE: OZONE GENERATORS

Ozone may be produced by chemical means, by the electrolysis of water and by the action of the electrostatic field on air or on oxygen.

Slow oxidations, as of phosphorus, produce ozone. The process is a curious one and has been studied by Schoenbein, who noticed that when certain substances are oxidized by air a portion of the oxygen combines directly with the substance undergoing oxidation, while another portion of the oxygen forms ozone. Thus ozone is formed during the oxidation of numerous substances. Schoenbein also enunciated the law that precisely the same amount of oxygen is converted into ozone as combines with the substance oxidized. This law has been verified by several other observers for phosphorus, aldehyde, triethylphosphine, turpentine, amylene and numerous other organic substances, and for sodium sulphite, ammoniacal cuprous oxide, etc., in the process of auto-oxidation.

About the only practical application, however, of the chemical production of ozone, has been by means of fluorin. Moisson has obtained fluorin by the electrolysis of anhydrous hydrofluoric acid. Fluorin attacks powerfully all organic materials and decomposes water, combining with its hydrogen to form hydrofluoric acid, and at low temperatures, the oxygen forms ozone. The reaction is as follows:

$$3\ H_2O + 6\ Fl = 6HFl + O_3$$

In the preparation of ozone by the decomposition of water by fluorin, the fluorin is introduced in a thin stream into the water, which is maintained at a temperature of 0 deg. cent.

Recent improvements in fluorin generators have made the method practicable but it does not compare in economy with the electrical methods of ozone production.

The Electrolytic Production of Ozone. Ozone is formed along with the oxygen in water electrolysis. The presence of ozone accounts for the low reading for oxygen obtained when the electrolyte is too strong in sulphuric acid and the current density too high.

The first recorded observation of ozone in water electrolysis was by Schoenbein in 1840. More recently ozone has been obtained by alternating-current electrolysis of acidulated water.

In some of the electrolytic processes at Niagara Falls the presence of ozone has been strongly manifest, though there is no recorded mention of its having been used for any industrial purpose.

In the production of ozone by electrolysis, the anode must be of some substance not oxidizable, such as platinum, gold, etc., and the electrolyte must contain no matter which is capable of combining with the ozone.

In certain special applications, ozone prepared by electrolysis seems to be more active and suitable than that prepared by the commoner electrical methods, but the reasons are obscure and the cases uncertain. The method is not economical and has found no general application, though higher concentrations are obtainable than by other ordinary procedures.

Electrostatic Production of Ozone. The common method of ozone production for industrial purposes is by the action of the electrostatic field on air or oxygen.

The types of machines that have been devised are almost without number, ranging from those utilizing the high-frequency discharges of the Oudin and Tesla resonators to those making use of the "effluve" or the silent discharge of a leaky condenser with or without solid dielectrics. The variations and the combinations of the fundamental types are too numerous to mention, even, and only a few of the more useful and striking examples will be described.

The ultimate theory of the electrical formation of ozone is still somewhat obscure and it may be said that whatever definite information there is on the subject is rather of a negative than of a positive character: *e.g.*, Warburg and Leithauser have shown that the process is not an electrolytic one. The equivalent weight of ozone is 24, and, therefore, if the process were an electrolytic one it would require the electrochemical equivalent, 96,540 coulombs, for the production of one mole, 24 g., of ozone. In actual practise, however, as much as 130 g. per kw-hr. has been obtained, which under the conditions of the operation corresponds with 240 coulombs only, or the equivalent of ozone has been obtained with about 44 coulombs. This number is far too different from the electrochemical equivalent to be a matter of experimental variation.

The view is generally held that the process is one of ionization and recombination. There appears a disassociation of the oxygen as soon as the action of the electrostatic field becomes sufficiently intense to cause ionization by collision, and there result numbers of ions from the disassociated molecules. These ions attach themselves to the molecules with which they must inevitably collide and thus form ozone which, on this view, may be composed of aggregates of odd numbers of atoms of the general formula, $O_{(2n+1)}$.

The relation between the quantity of ozone produced and the quantity of current has been the subject of considerable speculation, but no perfectly satisfactory hypothesis has been advanced. Warburg has advanced the theory that the ozone is formed by those electrons which have attained a certain critical velocity., *viz.*, that at which luminosity appears.

Ozone is an endothermic compound and, therefore, the equilibrium concentration is greatly increased under certain circumstances, as for example, the influence of the electrostatic field, especially if the temperature is kept low so as to lessen the destructive forces as compared with the constructive forces.

The silent discharge or "effluve" of the French writers, is the conduction of electricity through gases at low and moderate pressures. The phenomena vary with the electrical and physical dimensions, and with the conditions generally, of the electrical and gas pressure. The discharge is quiet and the gas attains a dark violet luminosity. If the pressure is comparatively low the discharge between a point and a plate will be of this nature, but the electrical polarity of the point exerts an influence. The discharge between plane parallel or curved concentric surfaces is generally of this character, and when a dielectric is interposed between the plates, the formation of sparks is effectually prevented.

The question as to whether or not a dielectric should be used has been the cause of considerable experimentation and discussion, but the general consensus of opinion at present is that the use of the dielectric increases the efficiency of the ozonator.

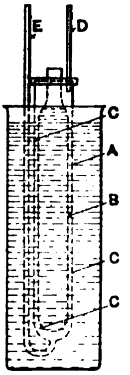


FIG. 1

Forms of Ozonators

One of the first ozonators with which experiments on anything like a large scale were carried out was introduced by Berthelot in 1876. This ozonator, Fig. 1, consists essentially of two concentric glass tubes *A*, *B*, closed at one end and forming between them the free annular space *C*, which is closed at the top by welding the two tubes together. Air or oxygen is admitted to the annular space by the inlet tube, *D*, and withdrawn at the outlet tube *E*. The inner tube *B* is filled with dilute sulphuric acid, and the outer tube, *A*, is plunged into a vessel containing the same, thus enabling the temperature of the system to be controlled.

The poles are formed by the fluid in the inner tube and that surrounding the outer tube. The electrical connections are made by means of two platinum wires dipping into the two acids respectively and connected to the terminals of the sources of current. When the potential difference is sufficiently high there is a luminous silent discharge in the gas in the annular space between the tubes and there is the formation of ozone.

The general principles of this ozonator have been retained in some of the later commercial types, *e.g.*, the Gerard ozonators.

The Siemens and Halske ozonators, Fig. 2, consist of a central metallic cylinder surrounded by an annular air space in which the electrical discharge takes place and through which the gas to be ozonized is passed. The outer boundary of the air space is a cylinder, concentric with the central core and in turn surrounded by a water jacket which serves to keep the temperature within proper limits. The potential is applied between the central core and the water surrounding the outer wall of the air space, and the latter may be of glass or of metal. In the latter case there is supplied a lining of glass which forms the dielectric. This type of ozonator has had considerable commercial application and is used in the installations at Wiesbaden-Padderborn, Saint Petersburg, etc. The whole ozonator is enclosed in a metallic case which is furnished with inlet and outlet tubes for the air and the ozone. The Gerard ozonator has appeared in several commercial forms which differ from each other in minor constructional details. It consists essentially of two concentric glass tubes about one meter in length, and the outer tube has a diameter of approximately 8 cm. The annular space between the tubes in which electrical phenomena take place varies from three to five mm. in the various modifications. The electrodes are metallic coatings affixed to the outer surface of the outer tube and to the inner surface of the inner tube respectively.

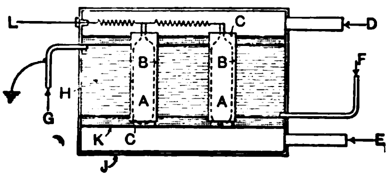


FIG. 2

A—inner electrode, *B*—outer tube, *C*—ozone space, *D*—air inlet, *E*—air outlet, *F*—water inlet, *G*—water outlet, *H*—water, *J*—outer casing, *K*—partition, *L*—high-tension lead.

An example of an ozonator without dielectrics is that of De Frise, Fig. 3. This consists of a trough, semicylindrical in cross-section and furnished with a water jacket for cooling. A glass cover closes the trough and from this are suspended a number of semicircular metallic disks which may have smooth or serrated edges. These disks are arranged in parallel planes and are spaced at about one cm. The flat edges are fastened to the glass cover and the curved edges together form a ribbed semicylindrical surface, which, when in position, comes to within about five mm. of the bottom of the trough, with which it is concentric. The

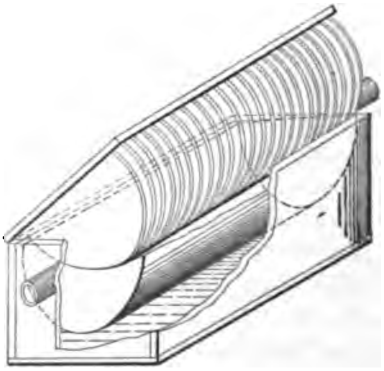


FIG. 3

electrical discharge takes place between the edges of these disks and the bottom of the trough, and the air to be ozonized is drawn through the space which intervenes.

There have appeared, from time to time, ozonators with devices for obviating the necessity for the solid dielectric. Otto has designed several in which the electrodes move with respect to each other, or in which one moves and the other remains stationary. Fig. 4 is a diagram of one of these. It consists of a metallic casing which forms one of the electrodes, and a series of metallic disks mounted parallel on a shaft by which they are rotated. The disks each have two sectoral windows, diametrically opposite each other, cut from them, and when assembled, form the other electrode. The disks are beveled at the edges, and the windows are staggered with respect to the disks which are adjacent. This arrangement assures that if a spark forms at any point, it will be drawn out and ruptured by the rotation of the disks.

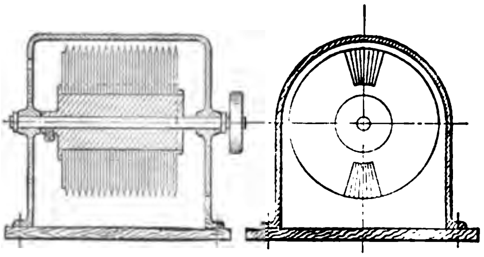


FIG. 4

Ozonators without solid dielectrics and with rotating electrodes have as yet enjoyed no very extensive application. The absence of the dielectric seems to favor the production of nitrous oxides notwithstanding the precautions to the contrary, and the extra power required to rotate the electrodes does not seem to be compensated for by any corresponding gain in another direction.

Besides the ozonators which have been mentioned there have appeared numerous others, as those of Andreoli, Tisley, D'Arsonval, Tindal, Otto, Vosmaer, etc., but all of the successful commercial types have tended to the same general design, namely, metallic electrodes with smooth surfaces and interpolated solid dielectrics.

All the ozonators which have been mentioned above are for the production of ozone on a large scale and at relatively high concentrations, and are in general intended for the purification of drinking water and for analagous industrial applications. Latterly, however, the subject of purifying and refreshing the air of localities which suffer from overcrowding, inadequate ventilation, and the introduction into the air of the noxious products of industrial activity, has engaged the attention of sanitarians to a considerable extent. From a consideration of the theoretical causes of the objectionable character of such air and the essential properties of ozone it has become evident to many experts that ozone offers a remedy for the conditions, and one which possesses many advantages of simplicity, efficiency and economy. There has resulted, in consequence, the development of numerous ozonators for the specific purpose of treating the air of populated spaces.

The requirements in these small ozonators differ in several important particulars from those demanded in the larger machines. The instruments are, in general, put into the hands of unskilled persons and they must, therefore, be simple, durable, self-contained and automatic to the greatest obtainable degree. They must be small, fireproof, free from danger and reliable in operation, and all of these properties must be possessed in a measure far surpassing that required in the larger machines intended for operation by skilled electricians. Under no circumstances must they produce nitrogen oxides, and this prohibition also precludes the employment of means for removing the objectionable by-products after they may have been formed in the machine.

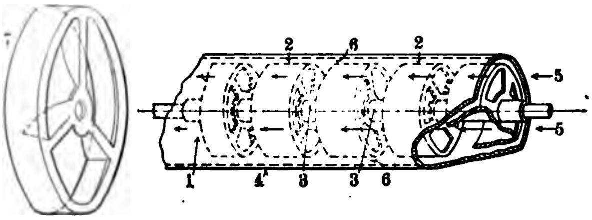


FIG. 5

1—glass tube; 2—aluminum cylinders, inner electrode; 3—spacing collars; 4—metal coating, outer electrode; 5—direction of air flow; 6—air-gap; 7—enlarged view of 2.

Most of these desiderata such as safety, durability, simplicity, space economy, etc., etc., may be obtained by operating at low voltages. To employ low voltages at the frequencies commonly met with in commercial installations, and at the same time to obtain the electrostatic field intensities requisite for the production of ozone, the length of the field in a direction normal to the electrode surfaces must be shortened. This shortening ordinarily has the disadvantage that it lessens the volume of air that may be treated with respect to a given area of electrostatic field, and consequently affects adversely the consideration of space economy. Fig. 5 shows a method by which the field has been shortened to a value limited only by the inability of the glass-blower to produce more accurate tubes, without at the same time curtailing the ozone production capacity of the ozonator. The cut represents one form of unit used in the General Electric air ozonators, an assembled machine being shown in Fig. 6.

Referring to Fig. 5, the potential is applied between the metallic coating of the glass tube, 1, and the metallic inner electrode, 2, which is formed of a series of cups of a special design. The electrostatic field is formed in the space, 7, which has a clearance of the order of 0.4 mm. so that with comparatively low voltages the potential gradient may be extremely high. The air to be ozonized is blown along the axis as shown by the arrows, 5, and the peculiar vane shape of the spokes of the cupped electrodes causes a constant intercommunication between the new air and that which has been ozonized in the ozone spaces.

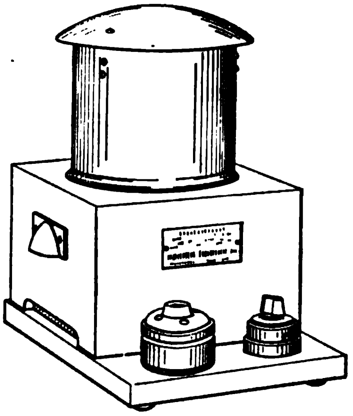


FIG. 6—ALTERNATING-CURRENT HOUSEHOLD OZONATOR.

Ozone is an allotropic form of oxygen with the formula O_3, as was established by Schoenbein. The nature of ozone was for a long time debated but the researches of Andrews and Tait, Marignac and De la Rive, Brodie, Fremy and Becquerel, and particularly those of Schoenbein, showed conclusively that when oxygen was converted into ozone, the volume was reduced one-third, and analysis failed to show the appearance of combinations with other elements. Ozone is a faintly bluish gas with a characteristic smell and it was this circumstance that led to its discovery. It has never been obtained in the pure state but is always mixed with oxygen from which it is derived.

Hautefeuille and Chappuis, on compressing ozone to 125 atmospheres at the temperature of boiling ethylene (−103 deg.), have obtained a dark blue liquid with highly magnetic properties. The compressed gas above the liquid was also of the same intense blue color, and both the compressed gas and the liquid were highly explosive. When the pressure is removed and the temperature allowed to rise, the liquid soon evaporates.

Ozone is relatively stable at ordinary temperatures when remote from organic or other oxidizable substances, but becomes unstable at elevated temperatures and decomposes into ordinary oxygen. The decomposition is instantaneous at 260 deg.

Ozone possesses enormous chemical activity as compared with ordinary oxygen, for the reason that it parts with the extra atom of oxygen very readily. It is an endothermic compound and the endothermic heat has been investigated by numerous chemists, including Berthelot, van der Meulen, Jahn and others. The mean value of the endothermic heat as obtained by numerous methods is 33.380 calories per gram-molecule.

Ozone is only slightly soluble in water. Recently, E. Maufang has investigated the subject and found that the solubility of ozone in water is proportional to the temperature and pressure, and conditioned by the chemical composition of the water; a concentration of 1.5 to 10 mg. per liter of water may be regarded as the solubility coefficient at ordinary temperatures (2 deg.—28 deg.)

The chemical analysis and the volumetric determination of ozone as worked out by Schoenbein in 1845 was the subject of some difference of opinion and discussion, but in 1872 Brodie verified the results and established the theory. Later, 1901, the discussion having again arisen, Ladenburg and Quasig covered the same ground with the same result, though they appear to have been unacquainted with the work of Brodie. Treadwell and Anneler, in 1905, checked all previous results and finally established the correctness of the method of analysis which is now in general use.

The analysis depends on the following reactions:

$$2\,KI + O_3 + H_2O = 2\,KOH + I_2 + O_2 \qquad (1)$$

and

$$2\,Na_2S_2O_3 + I_2 + 2\,KOH + H_2SO_4 = Na_2S_4O_6 + 2\,NaI + K_2SO_4 + 2\,H_2O \qquad (2)$$

which in actual practise reduce to the following volumetric equation:

$$1000 \text{ cc. } \frac{N}{10} Na_2S_2O_3 = \frac{O_3}{20} = \frac{48}{20} = 2.4 \text{ gm. } O_3. \qquad (3)$$

The commercial value of ozone consists in the fact that it is so powerful an oxidizing agent that many of the reactions of oxidation which take place with ordinary oxygen only on the addition of heat, may be effected with ozone without previous heating, and in a much shorter time.

The many applications of ozone have been adequately treated in previous publications* and aside from the purification of air and water they are of general interest to the chemist rather than to the engineer, and will not be dilated on here.

The fact that there was transacted about seven million dollars' worth of business in ozone apparatus in Europe last year indicates the trend of modern thought with respect to ozone.

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*M. W. Franklin in *N. Y. Medical Journal*, April 8, 1911, "Ozone." M. O. Troy in *General Electric Review*, August, 1911, "The Action of Ozone on Air."

DISCUSSION ON "OZONE: ITS PROPERTIES AND COMMERCIAL PRODUCTION" (FRANKLIN), SCHENECTADY, N. Y., MAY 17, 1912.

C. E. Skinner: From the mass of data already accumulated, there can be no doubt whatever as to the efficacy of ozone as a means of purifying drinking water. One of the Pittsburgh hospitals has an ozone plant installed, and the ozone is used not only for the purification of drinking water, but also for the disinfecting of the rooms and wards. Information in regard to this plant and from other sources has been such as to lead me to question whether there may not be harmful results from the use of ozone, as well as beneficial results. Shortly after the plant was installed in this hospital, one of the physicians experimenting with the ozone received the full strength of the ozone from the outlet tube, and was immediately rendered unconscious, and I believe there was some difficulty in reviving him, but so far as I was able to learn, no permanent injury resulted.

In another instance I was told that in working with ozone in connection with some therapeutic experiments, extreme nausea sometimes followed the work when the experimenter had been in the room with only a relatively small concentration of ozone for some length of time. I would therefore like to ask Dr. Franklin whether or not the strongly concentrated ozone, as in the first case, or smaller amounts as generated by an ozonator in a small room, for example, might not be injurious to persons compelled to breathe the air carrying this ozone.

Matthew O. Troy: As Dr. Franklin has indicated, the production and application of ozone has been developed to a high degree in Europe and abroad generally. Looking at the commercial aspect, I understand that the sale of ozonizing devices in Europe last year amounted to $7,000,000. It is not, therefore, a new subject. De la Coux has written a volume of 475 pages, covering in great detail the application of ozone in therapeutics, and much has been written in the scientific journals concerning its application to the industrial arts and the sterilization of water and air.

Ozonation received an impetus in this country a few years ago when several companies were organized for promoting the application of ozone to the purification of city water supplies. These companies failed from one cause or another, but it was probably not due to any defects in the general scheme of such applications, as the process has been made a commercial and practical success in many of the European cities. It is my belief that some company will again take it up in America and make a success of it.

The production of ozone by electrical means has superseded all other processes. It therefore becomes a problem for the electrical engineer and it is proper, therefore, that the paper which has just been read should have been presented before the

American Institute of Electrical Engineers, and I hope we may have more papers of an even broader scope presented in the near future.

What we need in America today is an abstract study by engineering bodies of the facts pertaining to ozone. It needs to be investigated by the electrical, sanitary, and ventilating engineers, by the medical fraternity in general and, in fact, by all of the engineering and scientific bodies which cover any of the diversified fields in which ozone finds an application.

Until recently the sterilization of air by ozone has been given little consideration in America, except on the basis of patent medicine quackery. There were a few devices on the market, poorly designed, not backed up by scientific investigation and exploited very much in the same manner as a patent medicine. The work was not undertaken in such a way as to gain the support of the medical fraternity, nor to promote thorough investigation or an accurate compilation of facts. Reputable manufacturers in America are now trying to give ozone the status it deserves and place it on the high plane it occupies abroad. The applications are numerous, but might for convenience be classified in four divisions—the sterilization of liquids, purification of air, industrial applications and therapeutic applications. The electrical fraternity is not interested in therapeutic applications, except in producing satisfactory devices for the purpose. Scientific bodies, however, such as the chemical and electrical organizations, are particularly interested in the industrial applications. This field has been scarcely explored, except by a few isolated experiments, made rather at random, which indicate wonderful possibilities—for example, the application of ozone in the manufacture of linoleums and oilcloths, in the varnishing processes, transportation of fruits, preservation of meats, the aging of liquors and wines, the bleaching of fabrics, etc. All of the above applications are so rich in possibilities that it is difficult to cover them in a paper such as that just presented, or a discussion of the paper, but I do wish to appeal to the Institute and other scientific bodies to encourage investigation of the subject, and the development of devices for producing ozone and their application, so that America may take rank with European and other foreign countries.

I hope at no distant time to be able to look to the literature of our own country, and the discussions and activities of our own scientific bodies, for information which now has to be sought and procured abroad. I am, therefore, glad to have had Dr. Franklin's paper presented to this body on this occasion, which is, I believe, the first time the subject has been discussed before an electrical engineering organization, and I trust we will have more of similar papers in the future.

J. Lester Woodbridge: Some years ago I had an opportunity to inspect an ozonizing plant for the purification of water, which was established in Philadelphia. It consisted of a series of tubes each of which contained two strips of metal, provided with serrated edges, placed opposite to each other, edge to edge, across which a brush discharge was maintained by means of a combination of condensance and inductance arranged to transform from constant potential to constant current, no dielectric being interposed between the opposite points. A current of air was passed through the tubes, and ozonized by the brush discharge, and this was used for purifying the water.

I would ask Dr. Franklin whether that particular type of plant has made any further progress, or whether it has been entirely abandoned, and why.

I also learned, although I did not follow the matter up personally, that one of the difficulties in purifying water with ozone in certain cases was the fact that a large amount of vegetable matter in the water would seize the ozone first and use it up, before the ozone had an opportunity to destroy the bacteria, and I would ask Dr. Franklin if that is not one of the difficulties of purifying water in this way, where there is a large amount of vegetable organic matter in the water.

W. L. R. Emmet: I would like to ask Dr. Franklin whether there is any good means of knowing how much ozone we are getting, and what its quality is, whether it is free from nitrous oxide, and whether the ozonation of the air is completed, and also that of the water.

Many people are interested in knowing how water is sterilized by ozone. I do not know myself just how it is applied, but I should think it might be hard to get at every particle of water with certainty. I tried holding in the draft from the ozonator a glass with a little water on the surface of it which contained many microscopic organisms, to see whether there was any effect on these organisms. I could not see that there was any. They all seemed to relish it. I judge from this, that in sterilizing water, unless you go at it right, you might miss a few.

Milton W. Franklin: Referring to Mr. Emmet's experiment: Bacteria are minute unicellular structures, incapable of independent locomotion, and the slightest injury to the single cell which constitutes them results in death. The organisms which he observed were organized animalculæ of a relatively high order and therefore it would require large amounts of concentrated ozone in contact with them for a considerable period to cause their destruction. In the commercial purification of water by means of ozone the ozonized air and the water are brought into intimate contact by any of numerous processes whose aim is to divide the water finely as well as the air and to bring together, and to maintain in contact for a predetermined period, the particles of air and of water.

Referring to Mr. Skinner's question: Broadly speaking, anything which may be called a medicinal substance is a poison. It is something which, when introduced into the living organism, produces a physiological effect. If given in moderation, the effect is only beneficial, but if the amounts administered are excessive, the effects are those of a poison, in the accepted meaning of that term. Ozone may be classed with these substances; in moderation its use is to be commended, but in excess it would undoubtedly produce untoward symptoms. However, it is extremely improbable that ozone is liable to be given in overdose, as the warnings are so pronounced and so remote from the beginning of actual danger that nobody could persist in exposing himself in air that possessed even a small fraction of the amount capable of doing harm. In the sterilization of rooms the advantages of ozone are that it is nonpoisonous and that it is a gas. In the first place the elaborate precautions for sealing the room and for guarding against the harm which might be done by escaping cyanogen may be ignored, and in the second place the gaseous nature of the ozone insures that every crevice and corner in the room will be treated.

With respect to the presence of vegetable matter in water, if the amount is excessive, the removal of the vegetable matter by filtering before sterilizing with ozone will be found cheaper than removing it by ozone, though the latter may always be accomplished. The object of all filtering and purification processes is to produce the result sought cheaply and at the same time surely. There certainly can be no objection to the ozone process, if it accomplishes these ends, simply because it operates in conjunction with another process which alone does not suffice, but which, when combined with ozone, cheapens the application of the latter.

A paper presented at the 273d Meeting of the American Institute of Electrical Engineers, Schenectady, N. Y., May 17, 1912.

FREIGHT TRAIN TESTS ON AN ELECTRIC INTERURBAN RAILWAY

BY S. T. DODD

The following article is a brief discussion of a series of tests made upon electric locomotives pulling freight trains on the Fort Dodge, Des Moines & Southern Railway, and a tabulation of the results of those tests. The object of the tests was to obtain records under regular service conditions from which values could be calculated for power consumption, train resistance, acceleration, and other fundamental data, which could be used to check the figures ordinarily assumed in making calculations and to show the amount of variation from standard figures which could be anticipated in practise.

TRAFFIC CONDITIONS

The Fort Dodge, Des Moines & Southern Railway is an interurban road running from Des Moines to Fort Dodge, Iowa, with a branch to Rockwell City. There are in all about 120 miles (193 km.) of electrified track, of which a little over one-half is operated at 1200 volts. A map of the line is shown in Fig. 1. Fig. 2 shows a condensed profile of the section of the road from Boone to Fort Dodge, being the section over which the test trains were run. Distances given on the profile are in miles measured from the southern end of the line at Des Moines.

Having been built originally on a steam railroad franchise, the road is almost entirely on private right-of-way and the alignment is remarkably straight for an electric road. The greater part of the line is over rolling country with a series of short grades and level stretches, the maximum grade reached on this section being 1.1 per cent. There are two relatively short sections of the road where greater irregularities are to be found. These are the points where the line crosses the Des Moines river, between mileposts 46 and 53 and between mileposts 80 and 83.5. At these two points very irregular track

FIG. 1—MAP OF FORT DODGE, DES MOINES & SOUTHERN RAILROAD.

conditions are encountered, with curves of 8 to 10 deg. and grades running as high as 2.44 per cent.

The road, running as it does in a general north and south direction, crosses the main direction of the transcontinental traffic and intersects a number of important trunk lines, including the C. R. I. & P. Ry., the C. & N. W. Ry., the I. C. R. R., and others with which it interchanges traffic. The regular freight train each day goes down the line, stopping at each of these interchange points to set out cars and pick up cars for other points or for the terminus. Regular freight service consists, therefore, of a series of runs 5 to 10 miles in length, with a certain amount of switching service at each stop. In addition to this regular freight service is a large amount of switching service at the terminals and some extra or through freight.

ELECTRIC EQUIPMENT AND MOTIVE POWER

The section of the line over which the tests were run is operated at 1200 volts direct current (1300 volts at substation), some 600-volt sections being encountered at Boone, Fort Dodge and Fraser. Power is delivered to the line from substations distributed and equipped as follows:

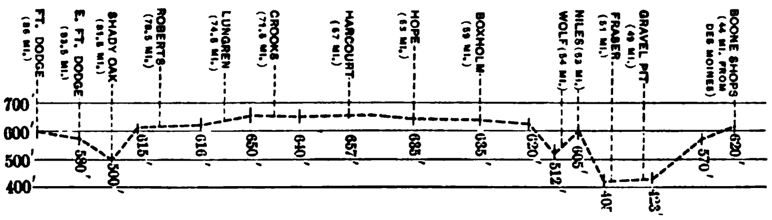

Fig. 2—Profile of F. D., D. M. & S. R.R., Boone to Fort Dodge.

Boone	600 volts.
Fraser	1200 volts and 600 volts.
Rinard	1200 volts.
East Fort Dodge	1200 volts and 600 volts.

Motive power consists of five 40-ton electric locomotives equipped for operation on either 600-volt or 1200-volt lines. There are in addition two locomotives which have been rebuilt by the railway company, and equipped with similar motor equipment, and three locomotives suitable for working on 600-volt lines only, which are used in the 600-volt yards at the terminus.

TESTING OUTFIT

The set of instruments used for carrying out the series of tests were all mounted in a box car and suitably wired up to flexible leads extending from one end of the car and ending in terminals by which they could be easily and quickly connected in the circuit of the locomotive to which the car was coupled. Figs. 3 and 4 show the interior of the test cars and the arrangement of instruments.

The set of instruments used consisted of the following:

One direct-current direct-reading voltmeter reading to 1500 volts.

One direct-current direct-reading ammeter reading to 300 amperes.

One graphic recording voltmeter and one graphic recording ammeter of the same capacities as the direct-reading instruments, with time marker clock and auxiliary marker pen indicating revolutions of the car wheel.

One railway type direct-current recording watt-hour meter mounted on shock-absorbing base, with a capacity of 1200 volts and 600 amperes.

The wiring was arranged so that the integrating wattmeter and the voltmeter were connected in the main trolley circuit of the locomotive and read the total voltage and watts delivered at the trolley wheel. The ammeters were connected in the circuit of one motor only, in order that the current readings might be translated directly into terms of tractive effort without reference to the controller position. If, on the other hand, the current readings had indicated the total current in the locomotive it would have been necessary to observe whether the controller was on the series or parallel notches and whether the locomotive was running on a 600-volt or a 1200-volt section of the line, in order to obtain a correct expression for tractive effort. It was assumed in all the readings that the current in all motors was the same at the same instant. This is true under ordinary conditions, due to the balanced combinations obtained by the bridge control. An exception will be noted when one pair of wheels slips in rounding curves or on slippery bits of track, throwing all the load on the other pairs. Some instances of this were noted during the tests, but except for such intermittent conditions, the assumption that total tractive effort can be read directly from current per motor is probably fairly accurate.

In preparation for a test, the car would be coupled to a train just back of the locomotive and the leads connected into the appropriate fuse block terminals. To make a complete test and obtain satisfactorily all the records, five observers were required, whose duties were approximately as follows:

PLATE XLVIII
A. I. E. E.
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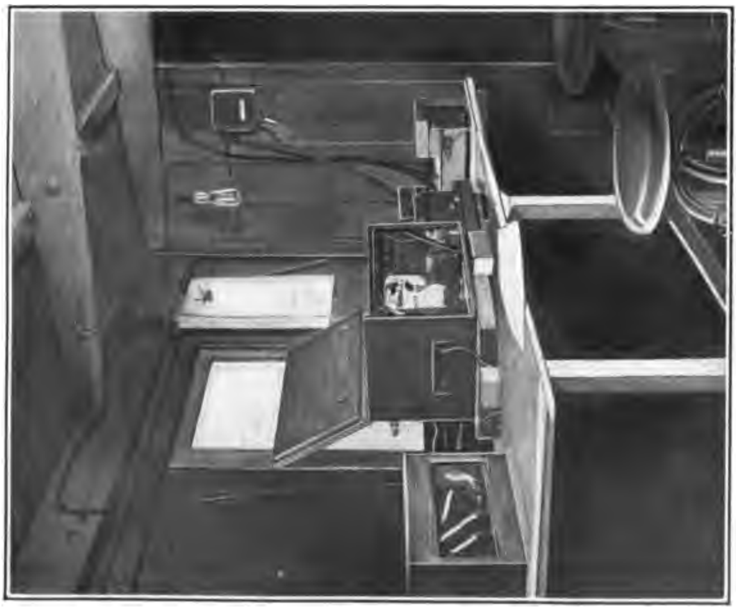
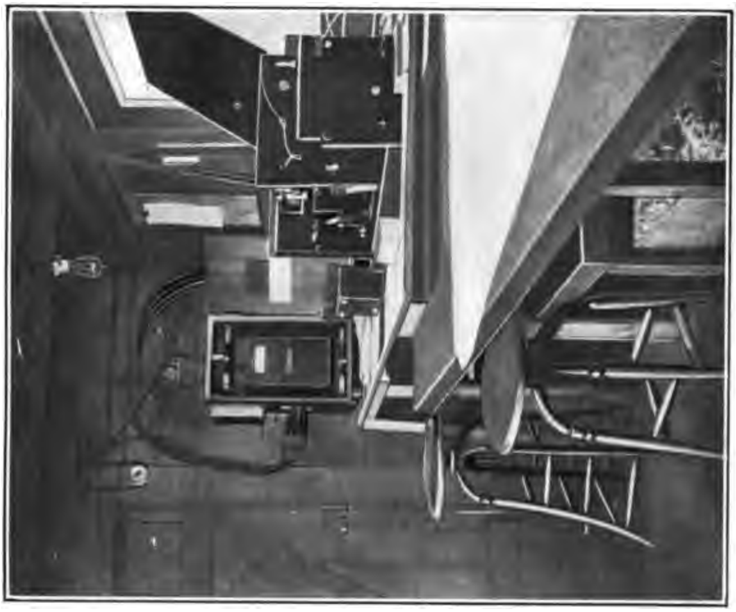


[DODD]

FIG. 3—INTERIOR OF TEST CAR.



[DODD]

FIG. 4—INTERIOR OF TEST CAR.

One man watched the recording ammeter, and a second the recording voltmeter. These observers maintained accurately the speed and excitation of the instruments, and made notes upon the record sheet which would tie together the various sets of observations.

A third man noted, by means of an auxiliary marker pen, the instant of passing given points such as stations, changes in grade, or other easily recognized points, and also took readings of the integrating wattmeter at points where changes in grade or character of traffic made these readings advisable.

A fourth man kept track of the train weight and his particular duty was to keep record at each station of the amount of switching and train movement.

The fifth man kept the log, keeping a continuous record of the time of all events, readings, notes, etc., which were reported to him by the other observers.

The test runs made by this testing car and crew were five in number. Table I gives in condensed form the logs of these tests, giving the chief facts as to stations between which runs were made and amount of time used for switching or waiting for connections. In this table, weights refer to gross tonnage, including weight of locomotive and test car. The figures in parentheses give the location of the station in miles from Des Moines at the southern end of the line.

Figs. 5, 6, and 7 are samples of the record sheets obtained in these tests. The curves on the lower section of each sheet show the current per motor and the total voltage. The curves on the upper section show the tractive effort of the whole locomotive as calculated from the current curves, and the speed in miles per hour.

Fig. 5 is a record obtained in test run No. 4 with a train of 752 tons gross weight running steadily over a broken profile. Figs. 6 and 7 show the same train on an up grade. Comment on these curves is hardly necessary as the course of events can be read directly from the record. The train is stalled at pole 2167 due to the slipping of the drivers. The locomotive takes the forward half of the train (373 tons) up the 1.5 per cent grade as far as pole 2213, where on a piece of slippery track the drivers begin slipping and it is necessary to back down to the starting point. At the second attempt the train is pulled through to the summit of the grade (pole 2227) although it will be noted the wheels slip again at the same piece of slippery track. The locomotive then

TABLE I
CONDENSED LOG OF TESTS

Test Run No. 1, Sept. 23, 1911

Time	From	To	Train wt.	Remarks
1:7 P.M.	Fraser (51)	Niles (53)	192	Up 2.44 % grade. Switching at Niles.
1:42	Niles (53)	Boxholm (59)	532	Switching and connections.
2:43:30	Boxholm (59)	Hope (63)	532	Switching.
3:11	Hope (63)	Crooks (71.5)	313	Connections.
3:47	Crookes (71.5)	E. Ft. Dodge (83.5)	313	Switching.
4:41	E. Ft. Dodge (83.5)	Ft. Dodge (86)	70	
4:50				Ft. Dodge.

Test Run No. 2, Sept. 23 and 24, 1911

Time	From	To	Train wt.	Remarks
10:7 P.M.	E. Ft. Dodge (83.5)		730	Two locomotives, mult. unit.
10:21:30				Stopped to cut train on 1.5 % grade.
10:31			407	Start on 1.5% grade
10:57			420	Start on 1.5 % grade.
11:16:30	Summit (80)	Roberts (78.5)	730	Drop one loco.
11:30	Roberts (78.5)	Harcourt sw. (68)	689	Switching.
12:40 A.M.	Harcourt sw. (68)	Harcourt (67)	353	Switching.
1:14	Harcourt (67)	Hope (63)	493	Switching.
1:56	Hope (63)	Boxholm (59)	491	Orders.
2:18	Boxholm (59)	Niles (53)	491	Switching.
2:52	Niles (51)	Boone (43.5)	351	
3:50				Boone shops

Test Run No. 3, Sept. 30, 1911

Time	From	To	Train wt.	Remarks
3:55	Fraser (51)	....	600	Run of 4 miles of which 1 mile is up 1% grade toward Boone.

Test Run No. 4, Oct. 2, 1911

Time	From	To	Train wt.	Remarks
1:19 A.M.	Fraser (51)	Niles (53)	327	Up 2.44 % grade Switching at Niles.
2:25	Niles (53)	....	752	
3:26	....	Harcourt (67)	...	Hot box 35 min. delay.
4:3	Harcourt 67)	....	752	
4:32	....	Lundgren (74.5)	...	Hot box 17 min. delay.
4:49	Lundgren (74.5)	....	752	
5:15	....	Ft. Dodge Hill (82)	...	Stop to cut train on 1% grade.
5:18	Ft. Dodge Hill (82)	E. Ft. Dodge (83.5)	373	Start on 1% grade.
5:56	Ft. Dodge Hill (82)	E. Ft. Dodge (83.5)	435	Start on 1% grade.
6:4				E. Ft. Dodge.

Test Run No. 5, Oct. 3, 1911

Time	From	To	Train wt.	Remarks
6:57	E. Ft. Dodge (83.5)	Summit (80)	420	Up 1.5% grade.

returns for the rear half of the train (435 tons) and pulls it through successfully at the first trial. Attention is called to this as it illustrates the variations in the hauling capacity of the same locomotive as affected by varying track conditions.

TRAIN FRICTION

An inspection of the test records shows a continually varying tractive effort corresponding to variations of grade, curvature and speed. No tests were made with the particular end in view of obtaining train friction, but a number of readings have been selected from the record in order to obtain a value of train friction at points where a fairly constant speed and current show that the effect of acceleration is eliminated. This value of train friction is not presented with a view of comparing in accuracy with the elaborate formulas and curves on freight car resistance which have been worked out by several steam railroads and which take into account the effect of speed, weather, temperature and other conditions, but it is presented as representing the average conditions during our tests and is to be accepted for comparative purposes only. It does, possibly, illustrate the variation in train friction and the values which may be expected in cars as picked up along interurban lines, and possibly illustrates this better than the more elaborate formulas I have referred to. The following table summarizes the results:

TABLE II

TRAIN FRICTION

Test Run No. 1	average of five readings	5.54 lb.*
" " No. 2	" " " "	8.9 "
" " No. 3	" " three "	9.6 "
" " No. 4	" " ten "	5.96 "
" " No. 5	" " two "	7.3 "
Summary of 25 readings		7.0 lb.

* 1 lb. =0.45 kg.

CURVE AND GRADE RESISTANCE

The records were inspected with the hope of ascertaining a value of the increased train resistance due to track curvature. Unfortunately no uniform results could be obtained. As said above, the track is in general straight, with easy curves, and the increased train resistance due to a part of the train being upon a curve was masked by other variable conditions. On the approaches to the Des Moines river valley, where a combination of grades and curves was encountered, the tractive effort was so variable that it cannot be expressed by a definite formula. The track curves are not compensated and the surging of the train set up by track variation and attested by the general impression obtained from riding upon and watching the train was shown very clearly by the periodic variation or pulsation of the tractive effort shown on the record. Table III is a tabulation of the tractive effort on such portions of the track. It gives for a number of points the maximum and minimum values of the tractive effort and the amount of the variation expressed in percentage, and in the last column gives the variation in apparent train resistance, the appropriate amount for the corresponding grade having been deducted.

I have omitted from this table the results from tests No. 1 and No. 3. The results of test No. 1 are not as reliable as succeeding tests on account of voltage fluctuations during the run and also on account of the inexperience of the observers during the first test. Test No. 3 was made on the one per cent grade from Fraser to Boone where the curves are compensated at a rate of 0.04 per cent for each degree of curvature. Either for this reason or because it was raining heavily during the test, which would result in a certain amount of track lubrication, the fluctuation of tractive effort which appears in other tests is not evident in this one.

An average of all the results of Table III, giving to each one the same weights, shows an average train friction of 13.4 lb. (6.1 kg.) per ton and a variation of train resistance above and below the average value of 15.8 per cent. In other words, it seems to be indicated by these tests that in figuring train resistance on tracks of this nature where a combination of grades and curves is encountered, it is fair to assume that the train resistance is doubled and to allow a variation in total train resistance of approximately 15 per cent above and below the average calculated value to compensate for surging set up in the train.

POWER CONSUMPTION

As previously remarked, records were taken of the amount of movement and weight of train handled in switching service.

One of the observers was intrusted with the particular duty of noting, during switching movements, each movement of the train and approximately the tonnage handled, estimating the tonnage from the number of cars and their condition as to load, and estimating the distance traveled from rail lengths or dis-

TABLE III—TRAIN FRICTION ON CURVES

Time	Curvature	Grade	Speed	Train weight	TRACTIVE EFFORT		Variation from average	Grade resistance	Train friction
	degrees	per cent.	mi. per hr.	tons	Total *	Lb. per ton	per cent		
					Test Run No. 2. Sept. 24, 1911				
10:34	4	1.5	6.5	407	17,000 to 25,000	42 to 61.5	19	30	12 to 31.5
10:39	7	1.5	6.5	407	17,000 " 25,000	42 " 61.5	19	30	12 " 31.5
11:0	6 and 4	1.5	6.5	420	16,000 " 22,000	38 " 52.5	18	30	8 " 22.5
11:4	6 and 8	1.5	6.0	420	17,000 " 27,000	40.5 " 54.0	22	30	10.5 " 34
						Average	19		20.2
					Test Run No. 4, Oct. 2, 1911				
12:43	6.5	1.08	5.5	445	17,500 to 19,500	39.6 to 44	5	21.6	17.9 to 22.4
1:24	6 and 4	2.44	12.	327	17,000 " 21,400	52 " 65.5	12	48.8	3.2 " 16.7
5:14	6	1.0	5.	752	18,000 " 20,500	24 " 27.3	7	20.0	4.0 " 7.3
5:22	6 and 7	.7	7.	373	7,000 " 9,500	18.8 " 25.5	15	14.0	4.8 " 11.5
5:37	7	1.5	13	373	13,500 " 15,500	36.2 " 41.5	7	30.0	6.2 " 11.5
6:0	6 and 7	.7	13.5	435	10,700 " 12,500	24.7 " 28.8	7.5	14.0	10.7 " 14.8
6:2	7	1.5	11.5	435	15,000 " 18,500	34.5 " 42.5	11	30.0	4.5 " 12.5
						Average	9.2		10.6
					Test Run No. 5, Oct. 3, 1911				
7:2 7:5	6	1.5	2.5	420	14,000 to 16,000	33.4 to 38.2	7	30.0	3.4 to 8.2
7:6 7:12	4 and 8	1.5	3.	420	13,500 " 20,000	32.2 " 47.5	20	30.0	2.2 " 17.5
7:18 7:22	7	1.55	6	258	8,500 " 15,000	33.0 " 58.2	27.5	31.0	2.0 " 27.2
7:37	8	1.5	6.5	218	7,500 " 12,000	34.5 " 55.0	23	30.0	4.5 " 25.0
7:39	7	1.5	13.5	218	8,500 " 11,000	39.0 " 50.5	13	30.0	9.0 " 20.5
						Average	18.1		11.9
					Average on all readings		15.8		13.4

TABLE IV—TONNAGE RECORD

Test Run no. 1, Sept. 23, 1911

From	To	Distance	Traling weight tons	Locomotive weight tons	Wattmeter reading kw-hr.	Kw-hr. freight	Kw-hr. switching	Ton-miles freight	Ton-miles locomotive	Ton-miles freight switching	Ton-miles locomotive switching
Frazer	Niles	2.2 mi.	151	41	74*	66		332.20	88		
		1000 ft.	15	41						2.8	7.8
		100 "	30	41						0.6	0.8
		750 "	430	41						61	5.8
		750 "	100	41						14.2	6
		200 "	85	41						3.2	1.6
		150 "	30	41						0.9	1.2
		250 "	15	41						0.7	2
		250 "	400	41						18.5	2
		1500 "	491	41	90		16			14.0	11.6
Niles	Hope	10 mi.	491	41	218	128		4910.00	410		
		1005 ft.	464	41						87.8	7.8
		25 "	310	41						1.5	0.2
		590 "	177	41						19.8	4.6
		100 "	457	41						6.7	0.8
		590 "	136	41						15.7	4.6
		100 "	192	41						3.6	0.8
		50 "	12	41						0.1	0.4
		230 "	94	41						4.1	1.8
		77 "	215	41						3.1	0.6
		152 "	272	41	233		15			7.9	1.2
Hope	E. Ft. Dodge	20.3 mi.	272	41	354.5	121.5		5,520	832		
		2570 ft.	272	41						132	19.9
		334 "	237	41						15	2.6
		210 "	334	41						13.30	1.6
		308 "	12	41						0.7	2.4
		460 "	29	41	364		9.5			2.5	3.5
E. Port Dodge	Ft. Dodge	2.5 mi.	29	41	370	6		72.5	102		
		Total				321.5	40.5	10,834.7	1432	429.7	91.6

Watt-hours per ton-mile: Freight 29.7; gross weight 26.2; freight switching 94.5; gross weight 77.8; all day service freight 32.2; gross weight 28.3.

*Wattmeter reading at start 8 kw-hr.

TABLE IV. (Continued).

TONNAGE RECORD

TEST RUN No. 2, SEPT. 23, AND 26, 1911

From	To	Distance	Trailing weight tons	Locomotive weight tons	Wattmeter readings kw-hr.	Kw-hr. freight	Kw-hr. switchings	Ton-miles freight	Ton-miles locomotive	Ton-miles freight switching	Ton-miles locomotive switching
E. Ft. Dodge	Rob. Hill	2.5 mi.	648	82	0			1,615	204.		
Rob Hill	Rob. Side	1.2 "	325	82				390	98.5		
Rob. Side	Rob. Hill	1.2 "	15	82				18	98.5		
Rob. Hill	Rob. Side	1.2 "	338	82				406	98.5		
Rob. Side	Roberts	1.3 "	648	82	98.4	196.8		843	106.5		
Roberts	Harcourt Switch	11.4 "	648	41	227	128.6		7,400	468		
		935 ft.	357	41						63.3	7.3
		470 "	15	41						1.3	3.7
		26 "	312	41	236		9			1.5	0.2
Harcourt Switch	Harcourt	1 mi.	312	41	250	14		312	41		
		675 ft.	15	41						1.9	5.2
		155 "	46	41						1.3	1.2
		100 "	77	41						1.5	0.8
		990 "	170	41						32.3	7.8
		1015 "	455	41						99	8.9
		545 "	61	41						6.3	4.2
		25 "	452	41	260		10			2.1	0.2
Harcourt	Hope	3.9 mi.	452	41	300	40		1,768	160.2		
Hope	Niles	10 "	450	41	404	104		4,500	410		
		935 ft.	155	41						27.5	7.3
		650 "	15	41	410		6			1.9	5.0
Niles	Boone Shops	9.7 mi.	310	41	552	142		3,000	398		
		Total				625.4	25	20,252	2,083.2	239.9	51.8

Watt-hours per ton-mile: Freight 31.0; gross weight 28.0; freight switching 104; gross weight switching 85.5; all-day service freight 31.75; all-day service gross weight 28.8.

TABLE IV (Continued.)

TONNAGE RECORD

TEST RUN NO. 4, OCT. 2, 1911

From	To	Distance miles	Trailing weight tons	Locomotive weight tons	Kw-hr. wattmeter	Kw-hr. through freight	Kw-hr. switching	Ton-miles through freight	Ton-miles locomotive	Watt.-hr. per ton-mile net	Watt.-hr. per ton-mile gross
Switching	Pole No.		404	41	1134		44				
Pole No. 470	584	2.06	286	41	1178	80.0		590	84.5	135.5	119.0
Switching				41	1258		22				
" 601	1159	10.30	711	41	1280	178.0		7,330	423	24.3	22.9
" 1159	1347	3.60	711	41	1458	44.0		2,560	147	17.2	16.3
" 1347	2003	12.40	711	41	1502	132.0		8,830	509	15	14.2
" 2003	2134	2.18	711	41	1634	4.0		1,550	89.5	2.6	2.4
" 2134	2167	.66		41	1638	13.7		471	27.2	29.1	27.5
" 2167	2213	.68	332	41			30.7				
" 2173	2230	.91	332	41		31.7		302	37.3	105	93.5
" 2230	2164	1.08	0	41							
" 2164	2229	1.06	394	41	1754	39.9		418	43.5	95.5	86.5
		Total				523.3		22,051	1,361		

Watt-hours per ton-mile: 23.7: gross weight 22.3.

tances between trolley poles. Table IV gives the details of this movement, and the same data are summarized in a slightly different manner in Table V. In the latter table the schedule speed and the watt-hours per ton-mile in switching and freight service have been summarized for all the separate movements of Table IV. In obtaining the schedule speeds all time at stations in excess of five minutes has been deducted. There were a number of instances during the tests where the train was held waiting for connections or train orders in excess of five minutes, and in all such cases time has been noted in a column by itself as " Time lost. " The " Time " noted in the column under " Switching " includes the time devoted to drilling cars and making up train, while the " Time " noted in the column under " Main Line " includes all station stops not in excess of five minutes. The " Schedule speed " is calculated from the corresponding time and distance. It is to be noted, however, that this schedule speed is reduced somewhat on account of time and distance lost in breaking trains and doubling on some of the heavy grades. This increases the distance actually traveled by the locomotive over that which would appear from the profile and the through mileage from one end of the run to the other. The increase in distance on this account is noted under the table.

TABLE V
POWER CONSUMPTION

		Main Line					Switching			
Test run	Total time-min.	Dist.	Time	Sched. speed	Watt-hr. per ton-mi.	Time lost min.	Dist.	Time	Sched. speed	Watt-hr. per ton-mi.
No. 1	222.5	35	152	13.8	26.2	33	2.23	37.5	3.6	77.8
No. 2	343	43.4*	294	9.0	28.0	15	1.24	34	2.2	85.5
No. 4	285	34.9†	169	11.3	22.3	95		21		
Average				11.4	25.5				2.9	81.6

* Add 2.9 miles for doubling.
† Add 3.85 " " "

Power consumption as discussed in this section includes all the power used in the locomotive, including that used for auxiliaries, lights, air-brakes, etc.

RATIO OF REVENUE FREIGHT TO GROSS WEIGHT

Table VI has been prepared showing for various portions of the test runs the total weight of the train and the proportion of this weight that represents car loading or revenue freight. In making up train weights only the gross weight of loaded cars was recorded, and in obtaining the net weight of freight, the weight of empty cars has been estimated in every case at 15 tons. Some slight error may be introduced by this fact, as the average freight car probably weighs a little more than 30,000 lb. (13,607 kg.). On the other hand, the weight of train includes the weight of the 15-ton test car, which would not be included in ordinary freight service, and this would tend to offset any errors caused by assuming too low a weight for empty cars. The average results of the table probably indicate very fairly what may be considered the proportion of revenue freight in mixed service such as was investigated in these tests. The table covers runs aggregating 109 miles (175.4 km.) and shows that the revenue freight carried in the cars is approximately 50 per cent of the train weight.

TABLE VI

RATIO OF REVENUE FREIGHT TO TRAIN WEIGHT

Test	Dist.	Weight		Ton-miles		Ratio
		Total	Revenue	Total	Revenue	
	miles	tons				per cent
No. 1	2.2	192	80	422	176	42
	10.0	532	317	5,320	3,170	59.5
	20.3	313	158	6,350	3,210	50.5
No. 2	5.0	730	291	3,650	1,450	40
	11.4	689	291	7,850	3,320	42.3
	1.0	353	145	353	145	41.2
	3.9	493	145	1,930	565	29.4
	10.0	491	143	4,910	1,430	29.2
	9.7	351	143	3,400	1,390	41.0
No. 3	4.0	660	337	2,640	1,350	51.0
No. 4	2.06	327	184	673	380	56.5
	30.26	752	489	22,800	14,750	65
No. 5	3.5	420	247	1,470	865	59
Total.....	109.32			61,768	32,201	52

ACCELERATION

In order to obtain an idea of the rate of acceleration acceptable in practise an examination was made of the test records covering the starting of the train at various stops. Many of these records could not be used as the basis of accurate calculation on account of lack of uniform current and other conditions caused by the slipping of drivers or other accidental occurrences. Ten of these starts have been selected in which the conditions were fairly uniform and the records plotted on a magnified scale. Of these Nos. 5, 6, and 7 are reproduced in Fig. 8. It should be noted in passing that the three accelerations shown in Fig. 8 correspond to the three starts shown in Figs. 6 and 7. The other acceleration curves have not been reproduced but the results of calculation of all of them are included in Table VII.

The following comments refer to this table:

Column 5 gives the rate of acceleration during the interval which is stated in column 4.

Column 6 expresses this acceleration in terms of pounds per ton.

Column 7 states the tractive effort for the total train due to acceleration alone.

Column 8 gives the total average tractive effort of the locomotive during the acceleration period, calculated from the tractive effort curves of the test record.

Column 9, under the heading " Friction, Actual," is obtained by adding the figures in columns 7 and 3 and subtracting their sum from the corresponding figures in column 8, and shows the tractive effort available for train friction after making due allowance for that used for acceleration and grade resistance.

Column 10 gives the train friction reduced to pounds per ton. This train friction during acceleration exhibits wide variations. This might be expected from the fact that, being derived from the other quantities, all the uncertainties in acceleration, grade and current data are finally reflected in the train resistance. In addition to this there actually exist wide variations in the train conditions at starting, due to variations in the condition of brake shoe application, cramping of trucks in track or against side bearings and other uncertain conditions which are largely eliminated after the train is running.

Column 11 gives the maximum value or surge of the tractive effort observed during the acceleration period.

Column 12 is derived from columns 8 and 11 and shows the ratio between the average tractive effort and the maximum surge. This ratio is largely dependent in any particular case upon the type of control used and the method of handling the controller by the engineer.

In discussing the results of this table it will be noted that

TABLE VII
ACCELERATION TEST

Curve No.	Tons train weight	Tractive effort due to grade	Acceleration				Tractive effort				
			Duration seconds	Miles per hour per second	Pounds per ton	Tractive effort	Average actual	Friction		Max.	Ratio
								Actual	lb. per ton		
1	445	0	26.0	0.173	16.6	7,400	16,500	9,100	2.04	24,300	0.68
2	327	0	16.6	0.349	33.6	11,000	12,200	1,200	3.67	17,300	0.71
3	752	0	30.0	0.133	12.8	10,000	17,420	7,420	9.87	20,300	0.86
4	752	—9024	20.0	0.143	13.8	10,300	12,625	11,350	15.10	15,500	0.82
5	373	+7460	20.8	0.144	13.8	5,160	21,400	8,780	23.50	25,000	0.86
6	373	+7460	23.5	0.225	21.7	8,090	17,400	1,850	4.96	23,500	0.77
7	435	+8700	29.0	0.127	12.2	5,320	17,400	3,380	7.78	20,000	0.87
8	660	0	42.0	0.171	16.5	10,900	9,860	?	?	12,500	0.79
9	258	+7740	26.0	0.115	11.0	2,850	16,400	5,810	22.50	19,700	0.83
10	218	+6540	28.0	0.193	18.5	4,400	14,520	3,940	18.10	17,100	0.85

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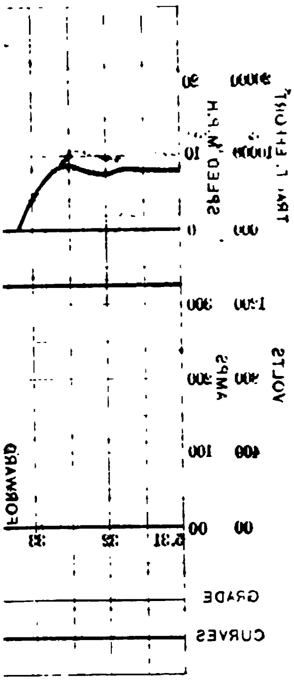
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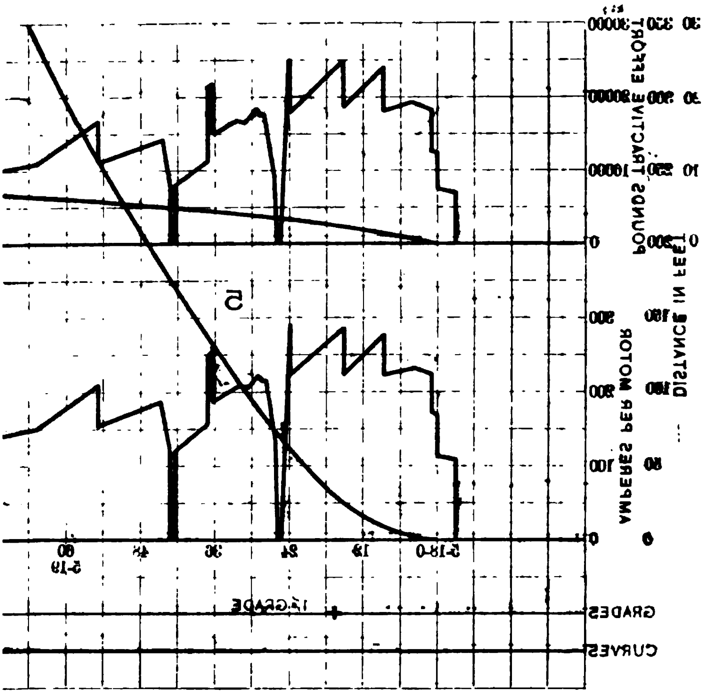
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although the results vary between rather large limits, certain conclusions may be drawn as to the allowances and the assumptions which may be made in calculating upon acceleration of freight trains.

a. Allowance must be made for an increase in train resistance above the normal. Apparently a resistance of 15 lb. (6.8 kg.) per ton is fair for such conditions as are represented by the tests under discussion.

b. The allowable rate of acceleration may be as low as $\frac{1}{10}$ mi. per hr. per sec. or 10 lb. (4.5 kg.) per ton. This, in combination with 15 lb. (6.8 kg.) per ton for train resistance, is none too low, as the train resistance falls off as soon as the train is under motion, giving a fair rate of acceleration over the range of the rheostat steps.

c. The available tractive effort for acceleration is not more than 80 per cent of the maximum tractive effort at the slipping point of the drivers. This means that if the slipping point is assumed at 30 per cent tractive coefficient, not more than 24 per cent tractive coefficient is available for acceleration.

Conclusion

In conclusion the writer begs to repeat what was said earlier, that the results of this paper are not intended to replace any standard formulas on railroad train operation, many of which have been carefully worked out and are supported by abundant experimental data. The paper is presented to show the results of actual tests in actual service and the amount of variation of those results from standard or average values.

The writer also wishes to acknowledge the courtesy of the officials of the Fort Dodge, Des Moines & Southern Railway Co., for extending their facilities to him, and to express his obligation to the students of the senior class in electrical engineering of the Iowa State College who assisted in carrying out the tests and working up the results embodied in this paper.

An address delivered at the Annual Meeting of the American Institute of Electrical Engineers, New York, May 21, 1912.

THE DEBT WE OWE TO HENRY AS A SCIENTIST

BY MICHAEL I. PUPIN

The name of Joseph Henry is connected with the most brilliant epoch in the history of the science of electricity. To appreciate it fully, let us briefly describe the state of this science prior to the beginning of this glorious epoch—I refer now to the discoveries of the eighteenth century. Stephen Gray's discovery of electrical conduction in 1729 was the broadest foundation for subsequent work. Franklin's discoveries and philosophical speculations in the realm of electrical phenomena gave a tremendous impulse to further research. Galvani's fortunate discovery of the existence of electric force in the contact region of heterogenous bodies closes this period.

Substantial progress was made during the eighteenth century, but the progress was, comparatively speaking, slow and laborious. The intellectual atmosphere of the eighteenth century was rather heavy and quiescent, as if foreboding the approach of a mighty storm.

The storm arrived; the intellectual forces which, like a mountain torrent, broke loose during the French Revolution, and threatened to unhinge every human structure, receded rapidly to their natural channels. The torrent seemed to have washed away every impediment to rapid intellectual progress, and a vigorous advance was started in every direction of human thought. The triumphant forward march of the science of electricity begins now. Volta (1799) discovers the voltaic cell and teaches mankind how to generate electricity in motion. Oersted (1819) discovers the magnetic force exerted by electricity in motion, and Ampere a year later (1820) formulates the fundamental law connecting this magnetic force with the electrical motion producing it. We have here three giants, Volta, Oersted and Ampere, accomplishing more in twenty years than had been accomplished before in the science of electricity in 2500 years. This kind of work and accomplishment reminds one of the forge of Cyclops as described in Homer's Odyssey. Every stroke shakes the earth to its very foundation. This was, indeed, a stupendous advance, yet it was only the beginning of the great period of electrical discovery and revelation, the period inaugurated by Joseph Henry and Michael Faraday.

Helmholtz and Thomson pointed out many years ago that Oersted's discovery is much broader than Oersted or even Ampere ever suspected, and that it embraces phenomena which these men never dreamt of, the phenomena of electromagnetic induction; or, to use a more descriptive expression, the phenomena of electric forces generated by the motion of magnetism. But to infer, from the existence of magnetic forces produced by moving electricity, the existence of electric forces produced by moving magnetism, it is necessary (as Helmholtz and Thomson point out), to have a clear vision of the principle of conservation of energy. This vision did not appear until nearly thirty years after Oersted and Ampere had finished their work in electromagnetism. But even if this great principle had arrived prior to the days of Oersted and Ampere, I doubt very much if the astuteness of any human brain would have ever gone so far as to infer, by pure logic, electromagnetic induction from electromagnetism. A logical deduction of this kind would stand today without a parallel in the history of human thought.

The fact that we can, today, in the light of the principle of conservation of energy, see a direct logical connection between electromagnetism and electromagnetic induction, is the best proof that the discoveries of Henry and Faraday furnish one of the most brilliant illustrations of the great power of the principle of conservation of energy.

But Henry's experimental work and Faraday's experimental work had to be done, and their great discoveries had to be made in the very manner in which they made them, in order to reveal before our wondering eyes the beautiful phenomena of electromagnetic induction. Nature guards her secrets too well to reveal a whole world of most startling phenomena to a man who makes no other effort than academic deduction by logic and pure reasoning. Our knowledge of physical phenomena advances by consecutive experimental steps; there was no direct line from Oersted and Ampere to Henry and Faraday. We had to wait for Arago, who showed that electricity in motion magnetizes a steel needle, and we had to wait for Sturgeon, who showed that an electrical current circulating in a coil of wire wrapped around a horseshoe-shaped piece of steel made a magnet. This was the birth of the electromagnet in 1823. Henry was then a youth, 24 years of age, doing tutoring work in a private family in Albany, and in his leisure hours studying mathematics and reading such works as Lagrange's classical treatise on " Analytical Mechanics." He had never had, up to this time, an instrument for research in his hands, but in less than five years he became the foremost authority, and practically the only authority, on electromagnets. At that time (this was prior to the discovery of electromagnetic induction) the science and the art of the electromagnet was undoubtedly the biggest problem in physics, and the very fact that Henry chose this subject for his study proves that he was cast for a great physicist. Willard Gibbs, our great mathematical physicist, said once that the most essential difference between a great and a commonplace scientist can be seen in the quality of problems which they select. A great physicist knows a great physical problem when he sees it. The electromagnet was a great problem, because it led to the discovery of electromagnetic induction; this was the key, and the only key, which opened the door of the secret chamber within which nature guarded the secrets of electromagnetic induction. Henry found the key and he opened the door which revealed to our wondering eyes the phenomena of electromagnetic induction. At about the same time, and using the same key which Henry had invented, the electromagnet, Faraday, independently of Henry, opened the same door. There can be no doubt as to Henry's claim. Sturgeon said: " Henry has been enabled to produce a magnetic force which totally eclipses every other in the annals of magnetism, and no parallel is to be found since the miraculous suspension of the celebrated oriental impostor in his iron coffin."

Henry worked day and night making electromagnets that could lift thousands of pounds, and these magnets are still in existence at Princeton and at Yale. If the master-mind which constructed these magnets had not discovered electromagnetic induction, and at the very time when the discovery was made, it would have been a miracle far more wonderful than the discovery itself.

Henry, it is true, never pressed his claim seriously. But he never pressed a claim; he never claimed anything; he was as modest as an angel and as unselfish as a saint. Besides, electromagnetic induction was so wonderful, destined, as he says, "to form a new era in the history of electricity and magnetism," that he would not permit himself in so big a thing as that to stand as a rival of the great Faraday.

It is thirty years to a day since I first saw Henry's discovery. I was a student at Columbia at that time, very fond of Greek and Latin, in fact so fond of it that I devoted most of my time to the study of Greek and Latin and classical literature. At the same time I was fond of mathematics and of physics, and of chemistry, and there was a doubt in my mind whether, when I graduated, I should take up as my life work classical studies or physics. One day I saw an experiment in the lecture room performed by the late Professor Rood of Columbia. He had a coil of wire, the terminals of which were connected to a galvanoscope, which was attached to the side of the wall so that the class could see the movement of the magnetic needle. The coil was in his left hand, and he had a magnet in his right hand. He moved the magnet a little bit, and off went the needle to one side, and then he moved the coil back, and the needle moved in the opposite direction. They say that magnetic needle moved because it is acted upon by the passage of electricity through the coil. Be that as it may, that needle, I am sure, was never as much thrilled as I was thrilled with that experiment, and I said "Good-bye Latin, good-bye Greek, I am going to study physics."

Imagine now how young Henry felt when he saw that magnetic needle thrill for the first time in the history of man when he moved the magnet in his modest laboratory at the high school in Albany. He himself tells what he thought of it, that it was destined to form a new era in the history of electricity and magnetism. You can see, then, why this man who was as modest as an angel and as unselfish as a saint could not thrust himself forward to dispute the discovery with a man as great as Faraday was at that time.

The same modesty and the same unselfishness which Henry displayed with regard to his claim as independent discoverer of electromagnetic induction, we find again in the case of his invention of the electromagnetic telegraph. Innumerable schemes had been proposed by various men, and at various times, to transmit signals by electricity. Even the electromagnetic scheme was originated in many minds and at various dates subsequent to Oersted's discovery, but nobody understood the problem as well as Henry did, and nobody succeeded in solving it until he solved it in 1831.

Barlow was one of the originators, but the distinguished physicist admits his failure when he says, in 1825: "I found such a sensible diminution (of the magnetic force) with only two hundred feet of wire, as at once to convince me of the impracticability of the scheme."

Wheatstone, another originator of the electromagnetic telegraph scheme, says this, in 1837: "It would not act, and could not act as a telegraph, because sufficient attractive power could not be imparted to an electromagnet interposed in a long circuit."

Wheatstone was not aware, in 1837, that Henry had demonstrated the practicability of the scheme in 1831, and that he wound up the description of his experiments in the Silliman Journal, by saying: "The fact that the magnetic action of a current from a trough is at least not sensibly diminished by passing through a long wire, is directly applicable to Mr. Barlow's project of forming an electromagnetic telegraph."

The cause of Henry's success is due to his complete understanding of Ohm's law, discovered in 1827. Barlow did not understand it because it did not exist when he made his telegraphic experiments in 1824, and Wheatstone did not understand it in 1837, because the law was made in Germany, and Wheatstone was an Englishman. Henry had no international prejudices. Besides, Ohm's law was not the only thing involved in a complete understanding of the electromagnetic telegraph problem; the self-inductive reaction of the electromagnet, and of the long line, had to be adjusted, and Henry's rule was, to make the resistance of the line and the self-inductive reaction of the line small in comparison with the resistance and the self-inductive reaction of the electromagnets; in other words, use an intensity magnet and an intensity battery when working over a long line.

This is the alpha and the omega of the electromagnetic telegraph, and it belongs to Henry and nobody else.

If the principle is true that that man is the inventor who first constructs and describes an invention in such a way that anybody skilled in the art can practise it, then surely Henry is the real inventor of the electromagnetic telegraph.

But Henry with his boundless modesty calls it Mr. Barlow's project, and never lays any claim to it. Nay, he even recommends, in 1856, that an extension of Morse's patent be granted to Morse. Verily, verily, such men as Henry are not made of ordinary mortal clay.

You can understand now the motives which prompted me twenty-two years ago to back up with all my heart and all my soul the proposition first advanced by my honored colleague, Professor F. B. Crocker of Columbia University, that the unit of self-induction be named after Henry. The Congress of Chicago adopted this proposition, and it is a significant fact that the motion was made by an Englishman, Ayrton, seconded by a Frenchman, Mascart, and the presiding officer was a German, the great Helmholtz himself.

I shall now close my remarks by placing before you another picture which shows in even stronger light the remarkable qualities of this truly great man. In 1842 he described before the American Philosophical Society his wonderful discovery of electrical oscillations accompanying a Leyden jar discharge. He traces magnetic action of these oscillations at a distance of thirty feet, transmitted there through walls and floors of a house. The detector is a steel needle which is magnetized by the transmitted oscillations. In this lecture Henry says: "The author is disposed to adopt the hypothesis of an electrical plenum, and from the foregoing experiments it would appear that the transfer of a single spark is sufficient to disturb perceptibly the electricity of space throughout at least a cube of 400,000 cubic feet of capacity; and when it is considered that the magnetism of the needle is the result of the difference of two actions, it may be further inferred that the diffusion of motion in this case is almost comparable with that of a spark from a flint and steel in the case of light."

Who does not feel in reading these lines that Henry knew instinctively that he was facing here a problem containing boundless possibilities? I am sure that he saw before him wireless telegraphy and the electromagnetic theory of light. There was no topic that he loved to discuss with his friends as much as the oscillating discharge of a Leyden jar. I can imagine how a man of his years (he was only 43 years of age at that time), and of his accomplishments, must have been eager to throw himself heart and soul into the study of this great and most fascinating problem which he had formulated himself. But, alas, his country calls him to other duties, and he bids good-bye to the academic groves of Princeton where he had spent so many happy hours in scientific study, contemplation and discourse with nature. He went to Washington to serve his country in organizing the Smithsonian Institution, and he knew that this meant adieu to Science for many years to come, and a bitter fight with crafty lawyers and cunning politicians who were eager to get hold of the Smithsonian Foundation, and fight about the definition of what Smithson meant when he said its foundation was for the purpose of advancing science and diffusing knowledge. The lawyers maintained that Smithson meant the building of libraries and filling them with law books, and the politicians said that Smithson wanted to buy seeds and send them to farmers, through the medium of the Representatives, so as to get new votes for Congressmen and Senators.

Now, what Henry did, you can easily guess, and what he thought you can easily guess. There was a struggle in which Henry engaged with his whole heart and soul for a number of years, and he conquered because on the one side there was the craftiness of the lawyer and the cunning of the politician, but on the other side there was justice and Joseph Henry. The Smithsonian Institution was then organized in accordance with these ideals, and we have today a splendid research laboratory, and we have a splendid museum. From the Smithsonian Institution nurtured by Joseph Henry sprang the magnificent scientific bureaus in Washington which are doing such splendid work. We have the National Academy of Science, and above all things we have a scientific spirit in Washington, the background of which is the spirit of Joseph Henry.

Joseph Henry loved his science, he loved his work, he loved his fellow man, and above all things he loved his country, and the duty he owed his country.

And now, Mr. Torchio*, the American Institute of Electrical Engineers could think of no better symbol to present to your Society than the bust of Joseph Henry. The American Institute of Electrical Engineers is aware that the Italian nation has great men, whom the Italians delight in honoring, and we know that in your Hall of Fame there is no man who can occupy a place with so much dignity as Joseph Henry. He is one of the

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*Mr. Philip Torchio, special representative of the Associazione Elettrotecnica Italiana.

very few men who can stand side by side and share companionship in your Hall of Fame with men like Galileo, Galvani, Volta and your Marconi of the present day, and with the bust of Joseph Henry, our Institute extends to your society its warmest greetings and its kindest regards.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 25, 1912.

CORONA LOSSES BETWEEN WIRES AT HIGH VOLTAGES

BY C. FRANCIS HARDING

Much has been written within the last few years upon the subject of atmospheric or so-called "corona" loss between wires at high voltages. Particular interest has been aroused in connection with this loss because of the fact that since the advent of the suspension insulator and the condenser type of transformer bushing the loss due to corona has become the limiting factor in the increase of transmission line voltages. The number of tests which have been made to determine the exact value of such loss under varying conditions of line construction, weather conditions, etc., which have been recognized to be free from a relatively large probability of error, has been too small to warrant final conclusions, particularly with regard to the accuracy of empirical formulas derived therefrom. The formulas suggested for the determination of corona loss and critical voltage have not been applied to other available tests nor a comparative summary made of such tests upon a common basis.

It is the object of this paper, therefore, first to set forth as a progress report the results of tests recently performed at Purdue University by a method differing in some respects from any previously published, and to compare the results obtained by various observers upon such a basis as to aid in the early confirmation of formulas which may be generally used in transmission line design.

EXPERIMENTAL TRANSMISSION LINE

The line upon which the tests were made was constructed for the purpose and was about 1380 ft. in length, made up of three spans of approximately equal length. Steel poles with 18-ft. crossarms supported the line through the agency of five-part suspension insulators. The insulators were so mounted that the wire spacing could be easily changed.

An insulator rack, Fig. 1, similar in all respects to the insulators upon the line, but containing only a few feet of line wire, was provided in order that the losses over the insulators might be separately measured and deducted. Jumpers surrounding the strain insulators were so designed that the line could be readily reached from the ground by means of a pole and connected to or disconnected from the insulator rack and feeder so that line and rack measurements could be made in rapid succession and therefore under the same weather conditions.

METHOD

The method employed was not unlike the one outlined by Peek,[1] although the introduction of some new details has been made therein which add many valuable data to the tests and possibly permit of greater accuracy in the final results.

The secondary of a 300,000-volt, 30-kw., 60-cycle transformer, previously constructed at the University, was opened at the grounded neutral, and a Rowland dynamometer, calibrated as an ammeter, and one of the elements of an oscillograph, were connected in series therewith. See Fig. 2. As the dynamometer had been previously calibrated with a potentiometer and standard cell, the effective value of the current wave obtained by means of the oscillograph was accurately known. An auxiliary coil having a diameter equal to that of an average secondary coil and so placed as to link the average flux cutting the secondary coils was connected in parallel with a voltmeter and a second oscillograph element. The middle point of the auxiliary coil was grounded. A spark gap was introduced into the secondary circuit, see Fig. 2, to protect against excessive voltage in case the latter should be accidentally opened. These ground connections together with those upon the magnetic circuit and frame of the oscillograph eliminated effects due to static charges which might have otherwise affected the calibration or reading of the instruments. The ratio of turns on the auxiliary and secondary windings was not depended upon to determine the secondary voltage, but a calibration curve was plotted between auxiliary coil voltage and secondary voltage as determined

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[1] See paper by F. W. Peek, Jr., TRANSACTIONS A.I.E.E., 1911, XXX, III, page 1889.

by spark gap measurement under all conditions of transformer loading and line spacing (see Figs. 3 and 4). The ordinate of the oscillograph voltage wave was therefore expressed in terms of secondary voltage between wires, while the current and voltage readings and waves combined enabled the power factor, power and wave distortion to be determined. As a check, readings in the primary were also taken.

The line spacing having been carefully adjusted, the calibration of the auxiliary coil voltage in terms of both spark gap distance (Fig. 3) and actual kilovolts taken from the A.I.E.E. standard spark gap curve was determined (Fig. 4), first with the line and feeders and secondly with the rack and feeders connected to the transformer. The difference between these two calibration curves, Fig. 4, due to the greater leakage flux in the transformer when furnishing the greater charging current demanded by the line, is quite marked and may have introduced errors in other investigations even when a portion of the secondary winding was used as an auxiliary exploring coil, if the above calibration with the secondary line spark gap was neglected.

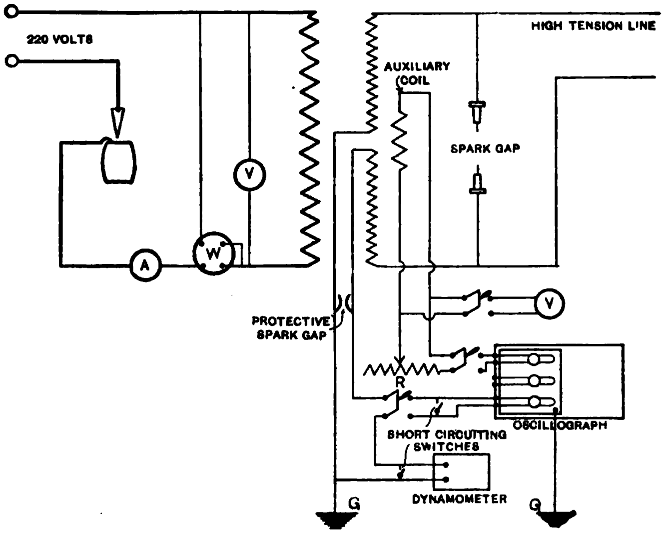


FIG. 2

With this information at hand eight or nine desirable voltages were selected for the test, and after the amplitude of the waves of voltage and current had been carefully adjusted upon the oscillograph screen by varying oscillograph field excitation, suspension tension and galvanometer circuit resistance in the case of the voltage wave, a film was exposed at each voltage to obtain a single point on the loss curve. By displacing the zero line somewhat the two wave forms at a single voltage with and with-

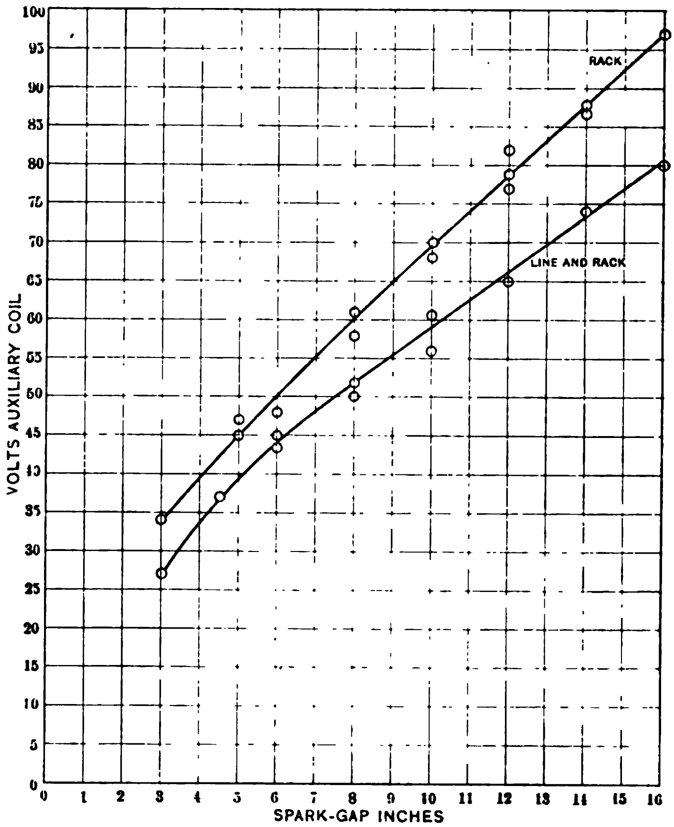


Fig. 3—Calibration Curve—Auxiliary Coil and Spark Gap.
No. 4 wire, 6-ft. spacing.

out the rack could be exposed upon a single film. Such a record is illustrated in Fig. 5. At the instant the film was exposed, readings of secondary current and auxiliary coil voltage, the latter being held constant during the test, were taken, together with primary voltage, current and power. To provide against a failure in exposure a tracing was also made of the wave

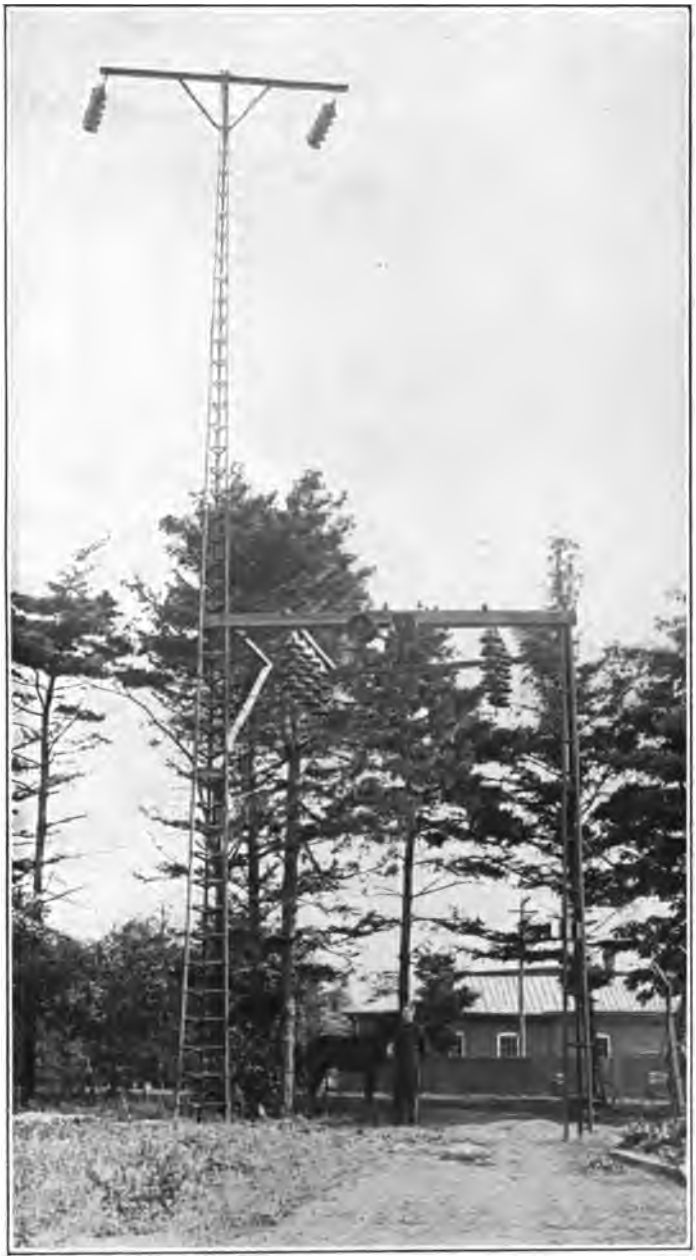
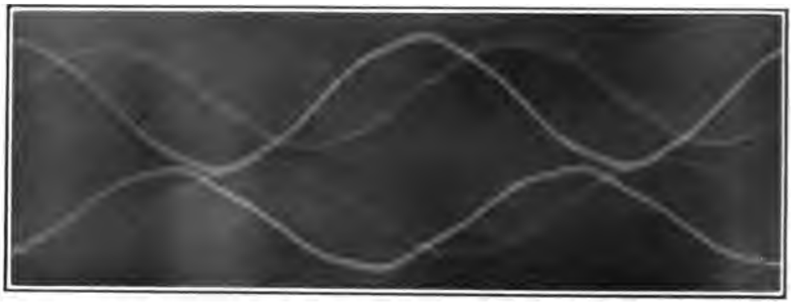


FIG. 1

[HARDING]



[HARDING]

FIG. 5

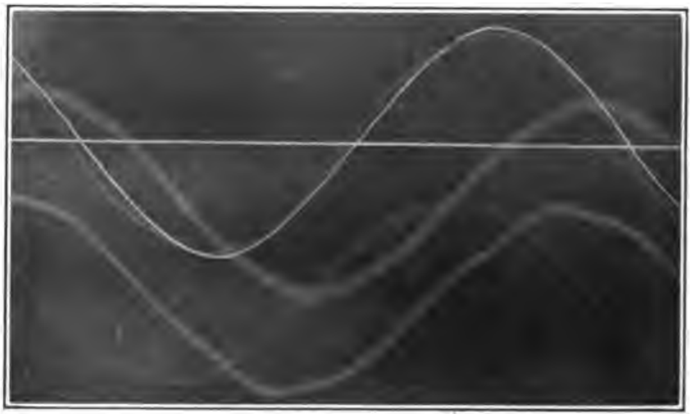


FIG. 6 [HARDING]

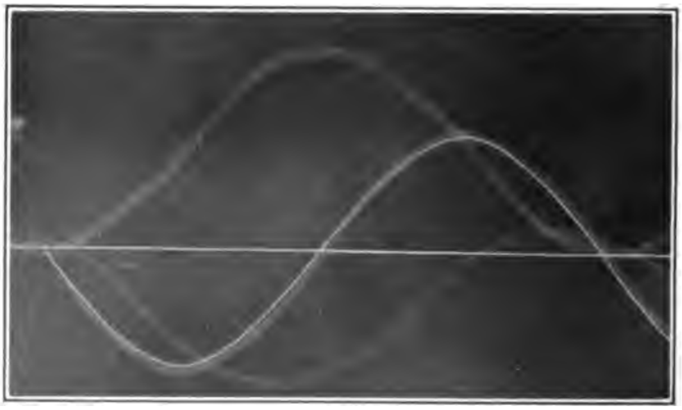


FIG. 7 [HARDING]

forms as they appeared upon the screen, but these tracings were used in but two points among all the curves obtained.

As wave distortion, if present, would require the calculation of an equivalent sine wave in order to make this method dependable, a careful study was made of the wave shapes obtained for both voltage and current. Only at very low values of line voltage was any effective distortion noticeable and the error thereby produced is seen by Fig. 6 to be small and located upon a portion of the loss curve where it is of little consequence. No calculations were therefore made of the equivalent sine wave except to determine Fig. 6. In Fig. 7 will be seen a comparison between

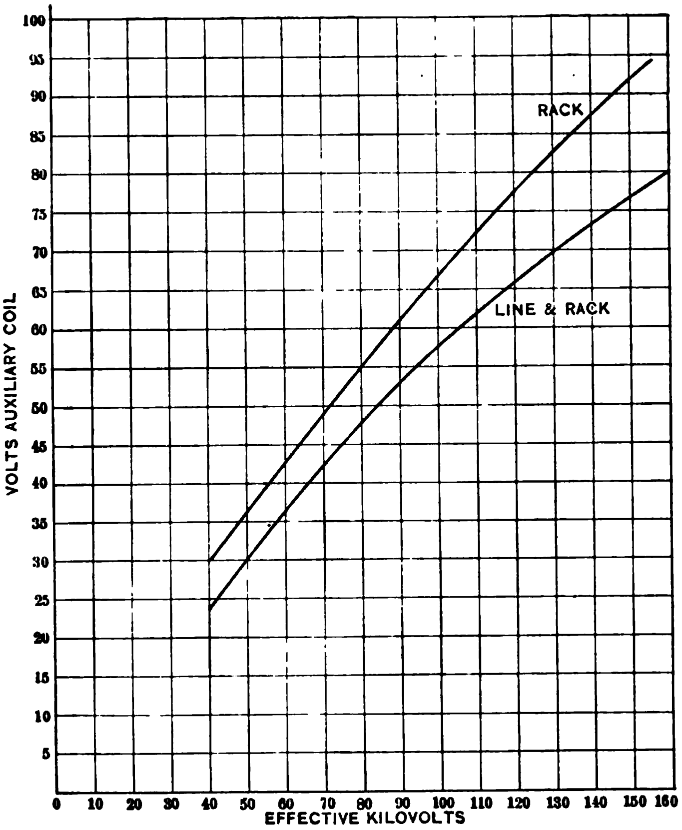


FIG. 4—CALIBRATION CURVE—AUXILIARY COIL READING AND SECONDARY EFFECTIVE KILOVOLTS.

No. 4 wire—6 ft. spacing.

a mathematically calculated sine wave and the actual wave obtained from the line test.

The zero line produced by the oscillograph was not depended upon, but the mean of the maximum deflections of the waves was used for drawing an accurate zero line upon the film. This line, as well as the displacements of the points of zero voltage and current, was very accurately determined by placing the developed film over a sheet of section paper with the peaks of the waves tangent to a given section line and noting the section line upon which the waves cut the zero line. The ratio of the average wave displacement thus measured to the average length of film required for a half cycle represented the ratio of displacement angle to 180 deg. The cosine of this angle was taken as the power factor.

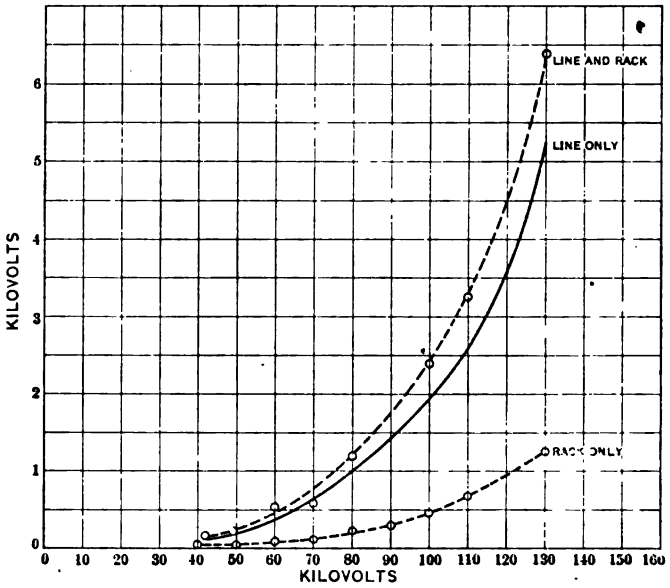


FIG. 8—ATMOSPHERIC LOSS—1000-FT. LINE.

No. 4 wire—6-ft. spacing—60 cycles—barometer 29.62 in.—temperature 41 deg. fahr.—humidity 63 per cent.

RESULTS

Curves showing the relation between corona loss and voltage between wires for No. 4 B. & S. solid copper-clad steel wires are shown in Figs. 8, 9 and 10, the broken lines indicating test results and the full line the actual loss upon the line proper after deducting losses on insulator rack and feeders. Fig. 10 also shows the increase of power factor with increase of voltage, indicating a rather marked change in slope beyond the critical voltage. Later tests indicated that the loss over the insulators was negligible and that the lower loss curve was made up principally of feeder losses. All losses were reduced to a standard length of line (two wires in parallel) of 1000 ft.

In order that a further study of these curves might be made the square roots of their kilowatt values (ordinates) were plotted in Fig. 11 against kilovolts as abscissas. It is evident that they obey the quadratic law both above and below the visual critical voltage, e_v, although the slope is different above that value, as would be expected. It is a significant fact that while the points thus plotted from the net loss curves of Figs. 8, 9 and 10, respectively, fall very accurately upon straight lines, none of the other curves involving more or less than the net losses between wires obey such a law. This seems to indicate that the method used is an accurate one.

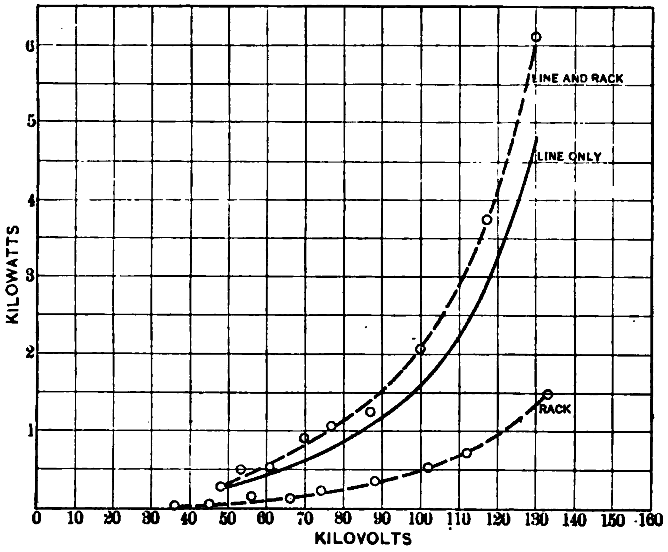


Fig. 9—Atmospheric Loss—1000-ft. Line.

No. 4 wire—8-ft. spacing—60 cycles—barometer 29.4 in.—temperature 56.5 deg. fahr.—humidity 69 per cent.

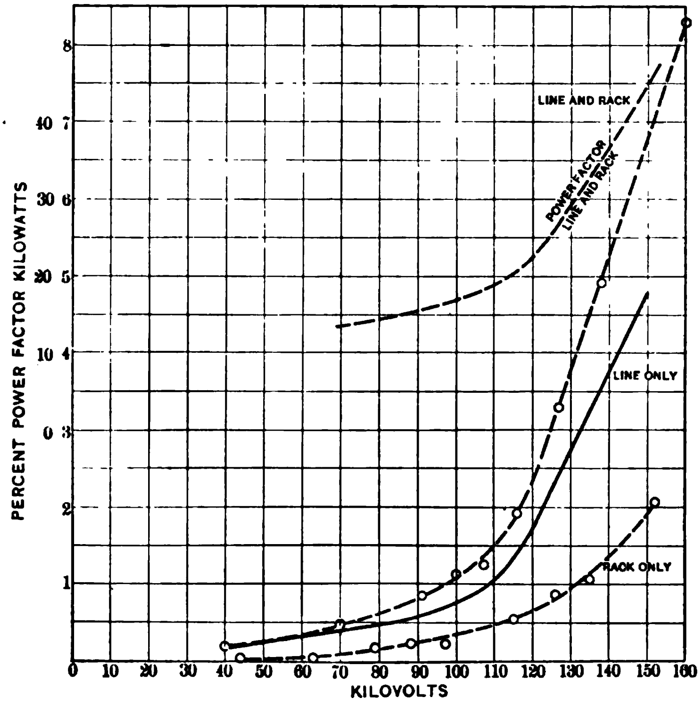


Fig. 10—Atmospheric Loss—1000-ft. Line.

No. 4 wire—10-ft. spacing—60 cycles—barometer 29.36 in.—temperature 49 deg. fahr — humidity 86 per cent.

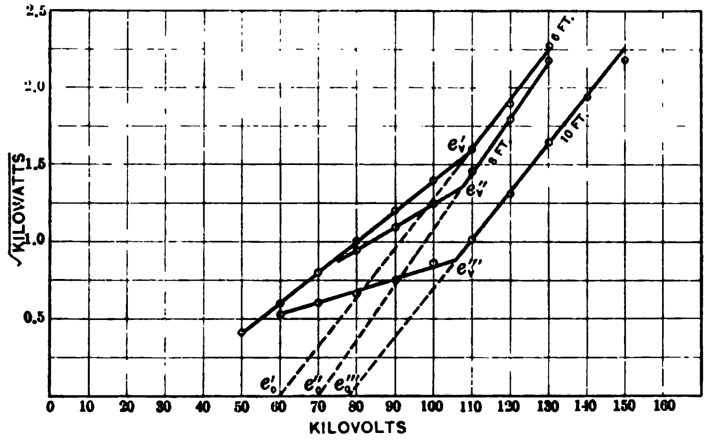


Fig. 11—Atmospheric Loss—Quadratic Analysis.

100-ft. line—No. 4 wire—6, 8 and 10 ft. spacings—60 cycles.

The application of the $\Sigma \Delta$ method to these curves results as follows:

TABLE I

Spacing	Critical disruptive voltage	Equation of curve	
		Below visual critical voltage	Above visual critical voltage
6 ft.	59.3	$kw = 0.00158\ (e - 14.9)^2$	$kw = 0.00404\ (e - 29.7)^2$
8 "	69.3	$kw = 0.00086\ (e - 7.5)^2$	$kw = 0.00512\ (e - 34.7)^2$
10 "	77.5	$kw = 0.00022\ (e + 6.45)^2$	$kw = 0.00388\ (e - 38.8)^2$

The accuracy with which these equations represent the experimental curves may be noted in Fig. 12, where the full line curves are taken from Figs. 8, 9 and 10 and the crosses indicate the points calculated by means of the above equations.

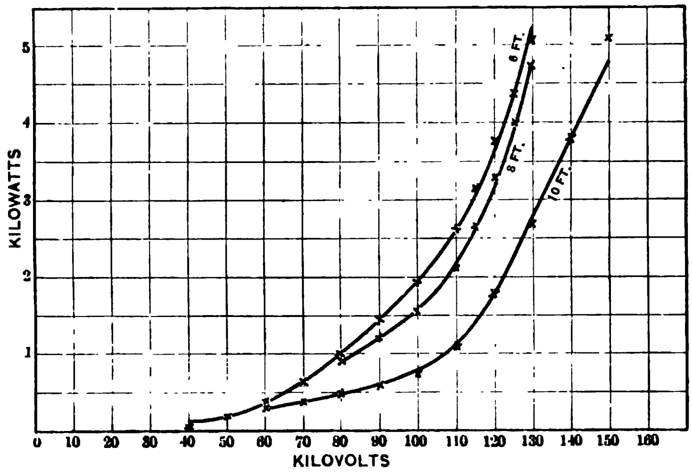


Fig. 12 —Atmospheric Loss—1000-ft. Line.
No. 4 wire—60 cycles.

A further check upon the formulas which have been proposed to determine corona loss[2] will be found below.

Let e_0 = effective disruptive critical voltage to neutral.
m_0 = constant depending upon condition of surface of wires = 0.93 for solid weathered wires.
g_0 = disruptive gradient of air = 21.1 kv. per cm. effective.
δ = air density factor.
r = radius of wire in cm.
s = distance between wire centers in cm.

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[2] *Ibid.*

whence

$$e_0 = m_0\, g_0\, \delta\, r \log_e \frac{s}{r}$$

Applying this formula to the test at the 10-ft. spacing, Fig. 10,

$$\delta = \frac{17.91 \times 29.36}{459 + 49} = 1.036$$

$$r = 0.259 \text{ cm.}$$

$$s = 305 \text{ cm.}$$

$$e_0 = 0.93 \times 21.1 \times 1.036 \times 0.259 \log_e \frac{305}{0.259} = 36.6 \text{ kv.}$$

e'_0 (between wires) = 73.2

e'_0 (from curve) = 77.5 kv.

The following table compares the values of effective disruptive critical voltage (e_0) calculated from the other tests by means of the above formula, and the empirical values determined from the curves.

TABLE II

Wire spacing	e_0 calculated	e_0 from curve
6 ft.	68.8 kv.	59.3 kv.
8 "	71.2 kv.	69.3 kv.
10 "	73.2 kv.	77.5 kv.

Although there is considerable departure from the calculated value in the test at six-ft. spacing, the tests at wider spacings check remarkably well when it is considered that the tests were carried on in an entirely different locality and under conditions of temperature and pressure different from those upon which the formulas were based.

But the comparison may be carried still further and the corona loss calculated from Peek's formula.

Let p = corona loss in kw.

k = constant = 344 in original formula.

f = frequency in cycles per second.

$$p = \frac{k}{\delta} f \sqrt{\frac{r}{s}}\, (e - e_0)^2\, 10^{-5} \text{ kw. per km. per wire}$$

$$\text{or } p' = 0.0021 \frac{f}{\delta} \sqrt{\frac{r}{s}}\, (e - e_0)^2 \text{ kw. per 1000 ft. for two wires.}$$

Again considering the ten-foot spacing,

$$p' = \frac{0.0021 \times 60}{1.036} \sqrt{\frac{0.259}{305}} (e - e_0)^2$$

$$= 0.00355 \, (e - 38.8)^2$$

if the value of (e_0) be taken from the test, or

$$p' = 0.00355 \, (e - 36.6)^2$$

it the calculated effective disruptive critical voltage be used.

The curves resulting from the calculations thus outlined may

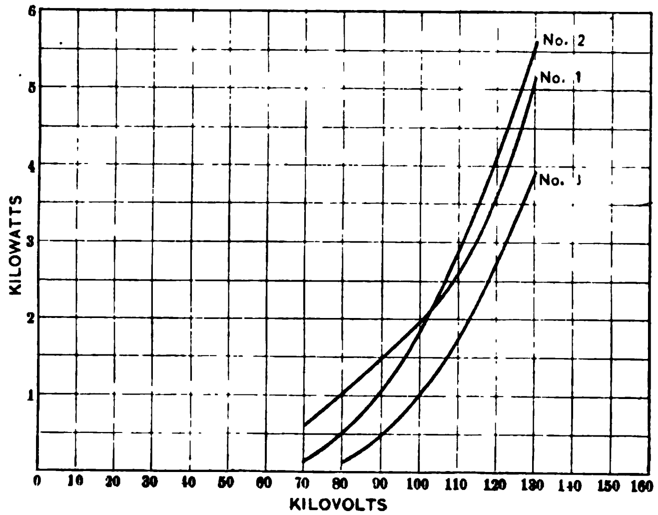

Fig. 13 –Atmospheric Loss—1000-ft. Line.
6-ft. spacing—No. 4 wire—60 cycles.
No. 1—Results of test.
No. 2—Calculated, e_0 from test.
No. 3—Calculated, e_0 (Peek's formula).

be compared with the experimental values in Figs. 13, 14 and 15, where it will be seen that the three curves fall remarkably close to one another above the visual critical voltage and especially at the 10-foot spacing, indicating that the calculated values are sufficiently accurate for any practical transmission line design.

Other Tests Compared

It is a significant fact that the corona loss curves resulting from the tests outlined in this paper obey a quadratic law both below and above the visual critical voltage, although the constant is different for the two portions of the curve. Peek's curve below the visual critical voltage was represented by a more complicated equation than the quadratic. A study of the results of other observers indicates that only an occasional curve obeys the quadratic law. For instance, but four of the twenty-nine curves determined by Mershon[3] are quadratic and these four, Figs. 14 and 15, represent tests upon very large stranded cables at comparatively low voltages so that but little of the curve above the critical voltage is available. The corona losses upon the Shoshone-Denver lines of the Central Colorado Power Company were found by Faccioli[4] to obey the quadratic law. The three groups of tests reported by Peek, Faccioli and the present paper not only offer an interesting comparison between results upon actual and experimental transmission lines, but, following as they do the quadratic law, the latter seems to have been fully established as the correct law of corona, especially as the tests mentioned were determined by measurements taken directly in the high-tension line under investigation and not in the primary circuit.

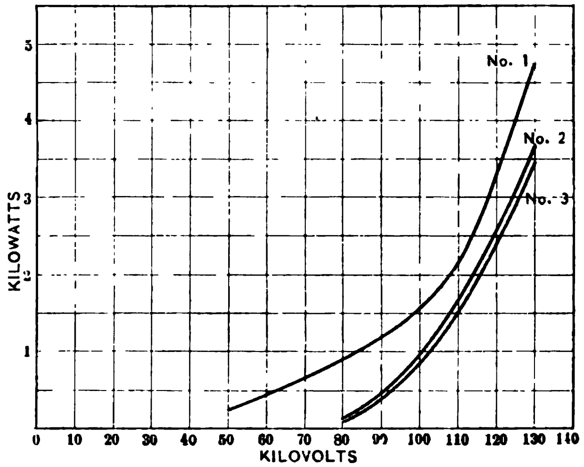

FIG. 14—ATMOSPHERIC LOSS. 1000-FT. LINE.

8-ft. spacing—No. 4 wire—60 cycles.

No. 1—Results of test.
No. 2—Calculated, e_0 from test.
No. 3—Calculated, e_0 (Peek's formula).

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[3] R. D. Mershon, A. I. E. E. TRANSACTIONS, 1908, Vol. XXVII, II, page 845.

[4] G. Faccioli, A. I. E. E. TRANSACTIONS, 1911, Vol. XXX, I, page 337.

In Fig. 16 will be found a comparison of the results of several tests upon both operating and experimental transmission lines, in which the losses have been reduced to a standard length of 1000 feet of two-wire line. Curves 1, 2 and 3, having nearly the same size of wire and spacing, maybe compared with oneanother. Such comparison indicates that Mershon's results are considerably lower than the others, while those of this paper check Peek's results fairly well, especially at the higher voltages. A similar study of curves 4, 5 and 6, which represent very similar line conditions, indicates that Peek's equation gives too low values of loss. This lower loss indicated by the curve resulting from Peek's equation as compared with test results upon operating lines seems to confirm the inference which might have been made from Figs. 13, 14 and 15, that values calculated from Peek's equation are slightly too low. The number of tests available does not justify a change in the equation, however.

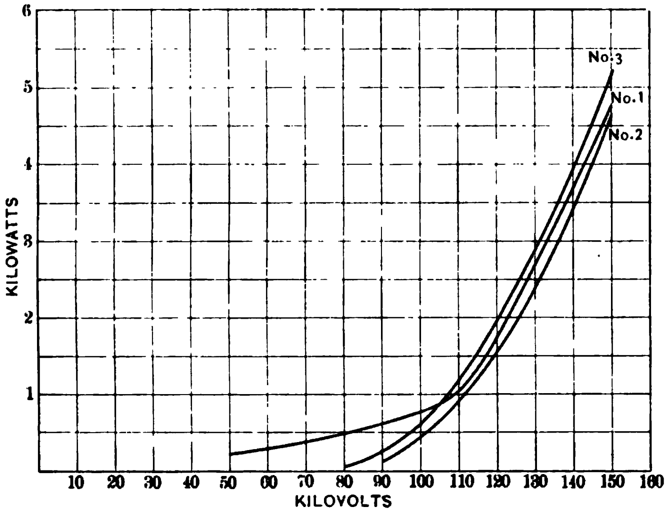

FIG. 15 —ATMOSPHERIC LOSS—1000-FT. LINE.

10-ft. spacing—No. 4 wire—60 cycles.

No. 1—Results of test.
No. 2—Calculated, e_0 from test.
No. 3—Calculated, e_0 (Peek's formula).

The use of copper-clad steel wire in these tests has already been mentioned. It may be of interest to note that the conductivity of this line was 43 per cent of that of a copper line of the same gage and that the impedance with the eight-ft. spacing was found to be 1.75 ohms, or 0.634 ohms per 1000 ft. of wire. The impedance of a No. 4 B. & S. copper line with the same spacing is found to be 0.82 ohms, or 46.9 per cent of the copper-clad line. With the higher voltages, longer spans and corona loss limitations, however, the increase in impedance may prove

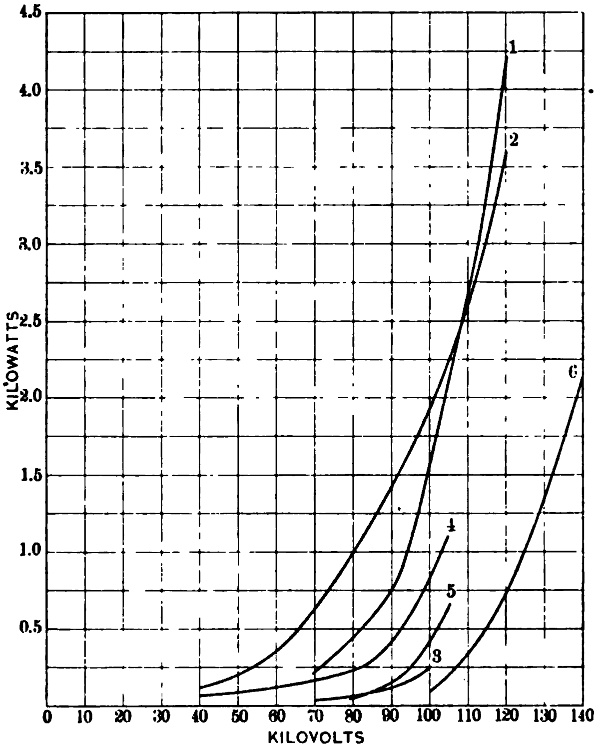

FIG. 16—ATMOSPHERIC LOSS—1000-FT. LINE.

Curve	Authority	Size wire	Spacing
1	Peek (test)	No. 8	6 ft.
2	Harding	No. 4	6 ft.
3	Mershon	No. 4 str.	7 ft.
4	West	1/0 and 1	10 ft. 4½ in.
5	Faccioli	1/0	10 ft. 4½ in.
6	Peek (calc.)	1/0	10 ft.

to be a negligible factor and the increased tensile strength found to be available for high-tension line construction.

CONCLUSIONS

1. Corona loss may be readily and accurately determined with instruments connected directly into the high-tension circuit.

2. The use of the oscillograph for this purpose is entirely satisfactory and furnishes many valuable data in regard to wave distortion and phase displacement not available by other methods.

3. The oscillograph may be accurately calibrated and films measured with sufficient closeness to guarantee dependable results.

4. When an auxiliary coil upon the step-up transformer is used, and probably in the case of the use of a section of the secondary winding to determine secondary voltage, it is necessary to calibrate such a coil with the secondary voltage for the various possible conditions of load and power factor.

5. Corona loss curves are parabolas, the constants of the equations being different above and below the visual critical voltage.

6. The equations of corona loss curves may be very closely approximated by means of the $\Sigma \Delta$ method.

7. Test values checked results calculated from Peek's formula for points above the visual critical voltage with a fair degree of accuracy, especially at the wider spacings between wires.

8. Variations from Peek's formula were in the direction of greater losses for a given voltage than those given by the formula. This was also found to be true of the tests which have been made upon operating lines, when the latter were reduced to a common standard for comparison.

The writer wishes to express his appreciation of the assistance rendered by Messrs. Phelps and Curtner, graduate students at the University, and to Messrs. Cox and Burke, who aided in the design and construction of the line and in taking readings. Recognition is also hereby expressed for the cooperation of the Locke Insulator Company, the Franklin Steel Company and the Duplex Metals Company, which enabled these tests to be successfully carried out.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

THE LAW OF CORONA AND THE DIELECTRIC STRENGTH OF AIR—II

BY F. W. PEEK, JR.

I. INTRODUCTION AND DISCUSSION OF PART I*

Part I of this paper,* presented at the A. I. E. E. Annual Convention in Chicago, gave the results and discussion of extensive investigations of corona formation and loss. These investigations consisted of power measurements on a short transmission line under all of the variable conditions of spacing, size of conductor storms, etc., met with in practise, supplemented with extensive laboratory investigations.

While the formulas given in Part I made it possible to predetermine accurately the corona characteristics of practical transmission lines over natural temperature and barometric pressure range and commercial frequency range, investigations were continued, and are still being continued, with a view of rationalizing the formulas, and getting at the fundamentals and fundamental mechanism of corona loss. The work of reduction of data obtained to date is still incomplete, and also it is not possible at the present time to include all that has been accomplished.

A considerable mass of new material, however, is given here.

All of this work has been made possible by engineering and test facilities afforded by the Consulting Engineering Department of the General Electric Co. under the general supervision of Dr. C. P. Steinmetz. Thanks are due to Messrs. C. M. Davis, J. L. R. Hayden, C. E. Magnusson, Don F. Smith and C. W. Stone for their active and valuable assistance.

For description of the apparatus and general method of test,

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* *The Law of Corona and the Dielectric Strength of Air*, TRANSACTIONS A. I. E. E., 1911, XXX, III, page 1889. Hereafter referred to as Part I.

see Part I. For convenience of reference the following short summary of equations, etc., is given from Part I.

The disruptive critical voltage is

$$e_0 = m_0\, g_0\, r \log_\epsilon \frac{s}{r} \text{ kv. to neutral,} \qquad (3)$$

where g_0 is the disruptive gradient of air in kilovolts per cm. at 25 deg. cent. and 76 cm. barometer, and is constant for all sizes of wires, frequencies, etc. If the effective value of g_0 is taken, e_0 is given in effective kilovolts,

where

r = radius of conductor in cm.

s = distance between conductor centers in cm.

g_0 = 29.8 kv. per cm. (maximum).

g_0 = 21.1 kv. per cm. (effective).

m_0 = a constant depending upon the condition of the conductor surface.

m_0 = 1 for polished conductors.

m_0 = 0.98 to 0.93 for roughened or weathered wires.

m_0 = 0.87 to 0.83 for cables.

Luminosity of the air surrounding the line conductors does not begin at the disruptive critical voltage e_0, but at a higher voltage e_v, the visual critical voltage.

The visual critical voltage e_v is much higher for small wires than the disruptive critical voltage, e_0; it is also higher for large wires, but to a lesser extent.

While theoretically no loss of power should occur below the visual voltage, e_v, some loss does occur, due to irregularities of the conductor surface, and seems to follow the probability law:

$$p_1 = q\, \epsilon^{-h\,(e_0 - e)^2} \qquad (4)$$

where q is a coefficient depending on the number of spots, and h is a coefficient depending on the size of spots.

Snow, sleet and rain losses seem to be of the same nature but frequently of far greater magnitude.

The visual critical voltage, e_v, is derived from the disruptive gradient g_0 by the equation

$$e_v = m_v\, g_0\, \delta\, r \left(1 + \frac{0.301}{\sqrt{r}}\right) \log_\epsilon \frac{s}{r} \text{ kv. to neutral} \qquad (5)^*$$

where

$$m_v = m_0 = 1 \text{ to } 0.93 \text{ for wires.}$$

$$m_v = \left\{\begin{array}{l} 0.72 \text{ local corona all along conductor;} \\ 0.82 \text{ decided corona all along conductor} \end{array}\right\} \begin{array}{l} \text{For seven-} \\ \text{strand cables} \end{array}$$

If g_0 (maximum) is used, e_v is obtained in maximum kilovolts.

$$g_v = g_0\,\delta\left(1 + \frac{0.301}{\sqrt{r}}\right) \qquad \text{(5a)*}$$

$$p = \frac{k}{\delta}\, f\sqrt{\frac{r}{s}}\left(e - g_0\, m_0\, r\, \delta \log_e \frac{s}{r}\right)^2 10^{-5} \text{ kw. per km. of single conductor.} \qquad (6)$$

e = effective kilovolts to neutral.
k = 344.
g_0 = 21.1 kv. per cm. (effective).
δ = air density factor = $\dfrac{3.92\, b}{273 + t}$
δ = 1 at 25 deg. cent. and 76 cm. barometric pressure.
b = barometric pressure, cm.
t = temperature, deg. cent.
r = radius of conductor, cm.
s = distance between centers of conductors, cm.
f = frequency, cycles per second.

The corona loss is

a. Proportional to the frequency f (over commercial range).

b. Proportional to the square of the excess voltage above the disruptive critical voltage, e_0.

c. Proportional to the square root of the conductor radius r, and inversely proportional to the square root of the conductor spacing.

The disruptive critical voltage, e_0, is that voltage at which the disruptive voltage gradient of the air is reached at the conductor surface. Hence, it is

a. Proportional to the conductor radius, r, and the $\log_e s/r$.

b. Proportional to the air density.

c. Depending somewhat on the conditions of the conductor surface as represented by m.

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* Proportional to δ with fair approximation over natural range of barometric pressure and temperature. δ enters also as a function in energy distance. See Section III of this paper.

The effects of various atmospheric conditions and storms on the critical voltage and loss will now be considered. Humidity or " vapor products " have no appreciable effect on either the critical voltage or the loss.

Smoke lowers the critical voltage and increases the loss.

Heavy wind has no effect on the loss or critical voltage at ordinary commercial frequencies.

The weather conditions that really count practically and which must be seriously considered in the design of transmission lines are as follows:

Fog lowers the critical voltage and increases the loss.

Sleet on the wires, or falling sleet, lowers the critical voltage and increases the loss. High voltages do not entirely eliminate sleet formation.

Rain storms lower the critical voltage and increase the loss. Snow storms lower the critical voltage and increase the loss. The effect of snow is greater than that of any other weather condition.

II. SUMMARY OF PART II.

1. *Influence of Temperature and Barometric Pressure on g_v and g_0 over a Wide Range.*

a. Visual corona starts at a lower voltage if the temperature is increased. Visual corona starts at a lower voltage if the barometric pressure is decreased. That is,

$$e_v = \phi\,(\delta)$$

where δ is the air density factor. If e_v' is the visual critical voltage at $\delta = 1$, over a short range of δ a fair approximation is: $e_v = \delta\, e_v'$.

b. Over a considerable range of air density our experiments show

$$e_v = m_v\, g_0\, \delta\, r \left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \log_e \frac{s}{r} \qquad (5')$$

$$g_v = m_v\, g_0\, \delta \left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \qquad (5a')$$

c. This means that the ***disruptive gradient*** varies directly with the air density factor δ, as would be expected, and as already shown in Part I,

$$g_0 = \delta\, g_0'$$

It also means that the energy storage zone to cause rupture extends

$$0.301 \frac{\sqrt{r}}{\sqrt{\delta}} \text{ cm.}$$

from the conductor surface, and, therefore, g_v does not vary directly with the air density. This is in accordance with the theory of Part I that energy is necessary to cause rupture.

d. The influence of variation of air density is the same over a very wide range whether the variation of air density is caused by change of barometric pressure or temperature.

2. *Influence of Frequency on* g_v *and* g_0. Between 40 and 100 cycles the influence of frequency on g_v and g_0, if any, is small, and less than the slight changes in wave shape in the testing transformer at different frequencies and which cannot be detected by the oscillograph.

3. *Spark-over and Corona on Polished Parallel Wires or Cylinders.*

a. Where s/r is less than 30 spark-over occurs before corona appears.

b. Where s/r is 30, either spark or corona may occur. This point is very unstable. If corona appears first the spark-over voltage e_s is slightly increased.

c. Where s/r is greater than 30 corona appears at e_v, then spark-over occurs at higher voltage e_s.

d. Above the point of intersection of the e_s and e_v curves plotted with spacing s, e_s follows approximately a straight line through the test range. The g_v curve is a straight line parallel to the s axis. The g_s curve is also very nearly a straight line which intersects the g_v curve at $s/r = 30$, and extended cuts the g axis at $g_0 = 30$ kv. per cm. This seems to be a further check on 30 as the disruptive gradient for air.

e. e_s is less definite than e_v and is greatly influenced by irregularities, somewhat by humidity, dirt, etc. For polished wires and constant spacing, e_s increases with decreasing diameter of the wire. When the conductor surfaces are coated with water, at a given spacing e_s is almost independent of the radius of the wire and approximately follows the needle gap curve. Oil on the conductor surface has a somewhat similar effect. *Water* on the conductor surface always very greatly reduces g_v. *Oil* on the conductor surface reduces g_v to some extent on large conductors, and by in creasing the radius an appreciable per cent raises g_v on small conductors.

f. For the test range it is difficult to determine whether the e_s or g_s curve with s more nearly follows a straight line.

(1.) On the assumption that g_s is in straight line—and this seems the most reasonable assumption—we may write:

$$g_s = 30\left(1 + \frac{0.01}{\sqrt{r}}\frac{s}{r}\right) \text{ kv. per cm. maximum}$$

This holds above the triangular point where s/r is greater than 30. When $s/r = 30$ it reduces to the visual corona formula

$$g_s = 30\left(1 + \frac{0.301}{\sqrt{r}}\right) = g_v \text{ kv. per cm. maximum}$$

Experimental points follow this curve well.

(2.) On the assumption that e_s is a straight line the expression takes the form

$$e_s = 3.4\, s + \frac{s+5}{2.5\sqrt{r}}$$

This curve is based upon the assumption that for a given spacing all sizes of wires would spark-over at the same voltage and when $s/r = 30$ and $g_0 = 30$, if there were no " corona resistance." When r_1 is the total radius of wire and corona, and g_0 = gradient at edge of corona, this voltage would be, at no " corona resistance ",

$$3.4\, s$$

However, our experiments show that the spark-over varies with size of conductor and the difference is something similar to a " corona drop " expressed by

$$\frac{s+5}{2.5\sqrt{r}}$$

or the total spark-over voltage is

$$e_s = 3.4\, s + \frac{s+5}{2.5\sqrt{r}} \text{ kv. maximum}$$

Assumption (1) is a closer approximation to experimental values.

The visual corona gradient for a conductor coated with a film of oil is

$$g_v = 19\left(1 + \frac{0.65}{\sqrt{r}}\right) \text{ maximum kv. per cm.}$$

The visual corona gradient for a conductor coated with moisture, as by rain or fog, is

$$g_v = 9\left(1 + \frac{0.815}{\sqrt{r}}\right) \text{ maximum kv. per cm.}$$

h. In concentric cylinders designed for maximum dielectric strength the ratio is not $R/r = \epsilon$, but is modified because g_v is a function of r.

i. Where corona forms before spark in concentric cylinders, as when r is very small compared with R, corona does not extend out to radius x when R/x = critical ratio for metallic cylinders and spark-over, but greatly increases the spark-over point, indicating grading or " corona resistance. "

4. *Disruptive Gradient* g_0.

That g_0 is constant and is 30 kv. per cm. is indicated by three entirely different methods.

1. By visual corona.
2. By spark-over.
3. By power measurements.

5. *Stroboscopic Study of Corona.* By the use of a stroboscope, a-c. corona discharge was observed on wires and needle points on the negative and positive parts of the wave.

a. To the unaided eye corona discharge often appears to extend completely across between points without arc-over. Examination through a stroboscope shows that the corona extends way out from the positive needle as a bluish white spray. The negative needle appears as a red point.

b. To the unaided eye corona on parallel wires appears as reddish beads more or less evenly spaced, with a bluish white needle-like fringe in between. If the wires are smooth the stroboscope shows the red beads on the negative, and a smooth bluish white glow on the positive. At abrasions or points the positive corona extends way out as very fine bluish needles. Without the stroboscope the eye sees the combination of the positive and negative.

c. In general, the positive discharge appears as fine bluish-

white spray or needles, while the negative discharge appears as reddish tufts. The discharge from points always gives the same impression as a stream of water being forced out under pressure from the positive, and gathering in at the negative.

6. ***Remarks.*** Many interesting points are observed and further discussed which cannot be taken up in this summary.

Practical Corona Formulas

(Revised and collected for reference.)

Disruptive critical volts (parallel wires)

$$e_0 = 21.1\, m_0\, \delta\, r \log_e \frac{s}{r} \text{ effective kv. to neutral} \qquad (3)$$

Visual critical volts and gradient (parallel wires).

$$e_v = 21.1\, m_v\, \delta\, r \left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \log_e \frac{s}{r} \text{ effective kv. to neutral} \qquad (5')$$

$$g_v = 21.1\, \delta \left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \text{ effective kv. per cm.} \qquad (5a')$$

Power loss (fair weather).

$$P = \frac{344}{\delta} f \sqrt{\frac{r}{s}}\, (e - e_0)^2\, 10^{-5}$$

$$P = \frac{344}{\delta} f \sqrt{\frac{r}{s}} \left(e - 21.1\, m_0\, \delta\, r \log_e \frac{s}{r}\right)^2 10^{-5}$$

kw. per km. single conductor. **(6)**

Power loss (storm).

Power loss (storm) is higher and can generally be found with fair approximation by assuming $e_0 = 0.80$ of fair weather e_0 in **(6)**.

Visual corona gradient—wires thoroughly wet (with fair approximation)

$$g_v = 6.4 \left(1 + \frac{0.815}{\sqrt{r}}\right) \text{ effective kv. per cm.}$$

Other Formulas. For spark-over formulas, corona in concentric cylinders, etc., see text.

Notation

$\delta = \dfrac{3.92\, b}{273 + t}$

b = barometric pressure in cm.

t = temperature in degrees cent.

f = frequency in cycles per second.

m_0 = irregularity factor.

= 1 for polished wires.

= 0.98 to 0.93 for roughened or weathered wires.

= 0.87 to 0.83 for cables.

$$m_v = \left\{ \begin{array}{l} 0.72 \text{ for local corona all along conductor} \\ 0.82 \text{ for decided corona all along conductor} \end{array} \right\} \text{For seven-strand cables}$$

= 1 to 0.93 for wires.

r = radius of wire in cm.

s = distance between conductor centers in cm.

III. Influence of Temperature and Barometric Pressure on Visual Gradient and Disruptive Gradient

In the former paper* it was shown that the visual critical gradient for parallel wires may be expressed in maximum kv. per cm.

$$g_v = g_0 \left(1 + \frac{k}{\sqrt{r}}\right) = 29.8 \left(1 + \frac{0.301}{\sqrt{r}}\right)$$

at the standard temperature of 25 deg. cent. and barometric pressure of 76 cm. Also, for changes in temperature and barometric pressure *over the natural range, a fair approximation is*

$$g_v = 29.8\, \delta \left(1 + \frac{0.301}{\sqrt{r}}\right)$$

Where δ is the air density correction factor and is unity at the standard temperature and pressure.

$$\delta = \frac{3.92\, b}{273 + t}$$

b = barometric pressure.

t = temperature.

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* *Law of Corona and Dielectric Strength of Air*—I.

On the theory that definite energy is necessary to start disruption or glow,* g_0 should vary directly with the air density factor δ. g_v, however, should not vary directly with δ, as the thickness of the energy storage film should also be a function of δ. Thus, we would suspect that the equation for g_v should be written

$$g_v = g_0 \, \delta \left(1 + \frac{k}{\phi(\delta)\sqrt{r}}\right)$$

Whether δ is varied by change of temperature or air pressure, the effect should be the same as long as the temperature is not so high that the air is changed chemically. This will be discussed more fully, later, under the head of " Rupturing Energy."

TABLE I

FOR POLISHED COPPER TUBE INSIDE OF BRASS CYLINDER

Test 195 $r = 0.953$ $R = 5.55$ cm

Observed values				Calculated from equation			
Kv. effective	t deg. cent.	b cm.	δ	g_v (max)	g_v' (max)	k	$k\sqrt{\delta}$
48.5	18	75.4	1.016	40.7	41.4	0.286	0.285
46.5	37	"	0.954	39.1	39.1	0.312	0.305
45.2	50	"	0.915	38.0	37.7	0.327	0.312
43.4	66	"	0.873	36.5	36.2	0.337	0.314
41.0	85	"	0.826	34.5	34.5	0.339	0.308
39.6	100	"	0.793	33.3	33.3	0.344	0.306
37.6	119	"	0.754	31.6	31.9	0.342	0.297

Temperature Tests. A series of experiments on visual corona was carried on over a temperature range of -20 deg. cent. to 140 deg. cent. (All tests in this paper were made at 60 cycles unless otherwise specified.) The apparatus is shown in Fig. 1. It consists of a polished wire in the center of a brass cylinder. The cylinder was placed horizontally in a large asbestos-lined " hot box. " Heating was effected by grids at the bottom of the box. The cylinder was shielded in such a way, and sufficient time was allowed to elapse after each change to get uniform temperature in the tube. Temperature was observed by a number of thermometers distributed in the " hot box."

After heating became uniform, yoltage was applied and gradually increased until glow appeared. The central con-

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* Part I, TRANS. A. I. E. E., 1911, XXX, III, pages 1939–1947.

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[PEEK]

FIG. 1

ductor was observed through a window placed in such a position in the front part of the box that the whole length of the conductor could be seen. It was found that it made no appreciable difference in the starting voltage whether or not the box and tubes were " aired out " after each test. Concentric cylinders were used in this test rather than parallel wires, as the apparatus is more compact and requires a much smaller " hot box."

Three sizes of brass cylinders were used, having inside radii of 8.89, 5.55, and 3.65 cm., respectively. The central conductor ranged in size from 0.059 to 0.953 cm. radius. I and II are typical data tables.

TABLE II

FOR POLISHED COPPER TUBE INSIDE OF BRASS CYLINDER

Test 194 $r = 0.476$ cm. $R = 5.55$ cm.

Kv. effective	t	b	δ	g_v (max)	g_v' (max)	k	$k\sqrt{\delta}$
41.0	—13	75.5	1.139	49.6	50.0	0.279	0.298
40.0	0	"	1.084	48.3	48.0	0.304	0.316
37.0	20	74.9	1.001	44.8	44.9	0.306	0.306
35.7	41	75.5	0.942	43.2	42.7	0.331	0.312
33.2	70	"	0.863	40.1	39.7	0.342	0.318
31.5	87	"	0.823	38.1	38.1	0.342	0.310
29.5	121	"	0.753	35.7	35.4	0.361	0.313
28.7	130	"	0.734	34.7	34.7	0.358	0.308

$$g_v = \frac{e_v}{r \log_\epsilon \frac{R}{r}} \qquad g_v' = 31\,\delta\left(1 + \frac{0.308}{\sqrt{r\,\delta}}\right)$$

$$\delta = \frac{3.92\,b}{(273 + t.)}$$

Columns 1, 2, and 3 are the observed values. For concentric cylinders the gradient at the surface of the inner cylinder is

$$g = \frac{e}{r \log_\epsilon \frac{R}{r}}$$

where e is volts between cylinders,

R is the inside radius of the outer cylinder,

r is the radius of the inside cylinder.

Column 5 gives the surface gradient for the voltage e_v calculated directly from observed values. Hence, columns 1, 2, 3, 4 and 5 are observed values. As can be seen from the tables, and as already noted, g_v for a given r is independent of R or s, but varies with δ.

By $\Sigma\ \Delta$ reductions of all of the data the following equation connecting g_v with r and δ was obtained:

$$g_v = g_0\,\delta \left(1 + \frac{r}{\phi\,(\delta)\;r}\right)$$

For concentric cylinder,

$$g_v = 31\,\delta \left(1 + \frac{0.308}{\sqrt{\delta\,r}}\right) \text{ maximum kv. per cm.}$$

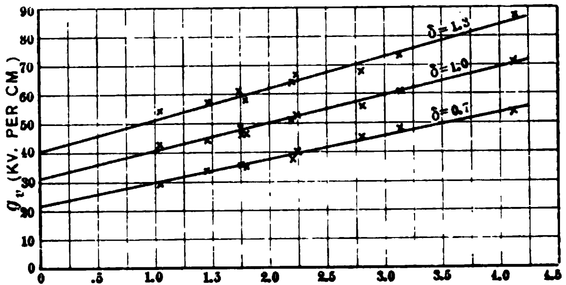

Fig. 2—Effect of Temperature upon Visual Corona; $\frac{1}{\sqrt{r}}$ — g_v Curves.

These curves show straight-line relation between g_v and $\frac{1}{\sqrt{r}}$ for constant δ, therefore at given δ, $g_v = g_0\left(1 + \frac{K}{\sqrt{r}}\right)$

For parallel wires,

$$g_v = 29.8\,\delta \left(1 + \frac{0.301}{\sqrt{\delta\,r}}\right) \text{ maximum kv. per cm.}$$

Referring to the tables, column 6 gives values of g_v calculated from the above equation. Column 5 gives observed values. It is seen that the difference is generally less than 1 per cent throughout the whole range. Column 7 gives values of k calculated from observed values of g_v and for $g_0 = 31$. In Figs. 2, 3 and 4 the drawn lines are the calculated values, while the crosses are observed values.

g_0 has a slightly higher value for wires in a concentric cylinder than for parallel wires. This does not mean that the strength of air differs in the two cases. For a wire in a concentric cylinder the field is balanced all around and uniform, and should give more nearly the true value. For parallel wires there is never complete balance, even where s/r is large. This gives g_0 an apparent value which is slightly lower.

Barometric Pressure. It is now interesting to see if the same law holds if the temperature is kept constant and δ is varied by changing the barometric pressure. Taking the curves by Whitehead*, in Fig. 5 the drawn lines are directly as plotted in

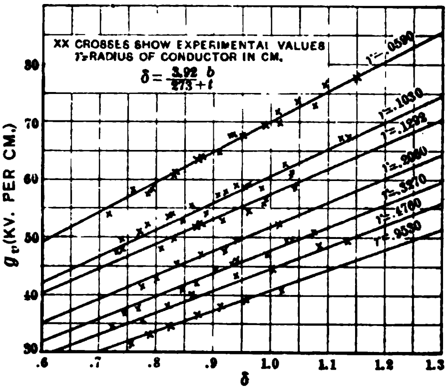

FIG. 3—EFFECT OF TEMPERATURE UPON VISUAL CORONA; δ-g_v CURVES.

Curves are drawn from calculated values, from $g_v = 31\delta\left(1 + \frac{0.308}{\delta r}\right)$

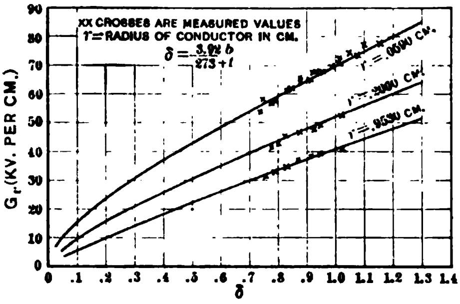

FIG. 4—EFFECT OF TEMPERATURE UPON VISUAL CORONA; δ-g_v CURVES.

Curves drawn from equation $g_v = 31\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)$

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* *Electric Strength of Air—II* (Figs. 6 and 7), J. B. Whitehead, TRANSACTIONS A. I. E. E., 1911, XXX, III, pages 1877–1879.

"*Electric Strength of Air*—II." The circles are points calculated from the equation

$$g_v = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)$$

The check is quite remarkable, and the law seems to apply equally well for temperature or pressure.

IV. INFLUENCE OF FREQUENCY ON VISUAL GRADIENT

The effect of frequency on g_v for the practical range of 25 to 60 cycles, if any, is very small and can be neglected. A few measurements are shown in Fig. 6. For the test range it is difficult to tell whether the slight variations are due to changes in wave shape too small to be detected by the oscillograph, or to frequency. The points show a tendency to decrease with increasing frequency. There is a possibility of frequency entering thus as a function in

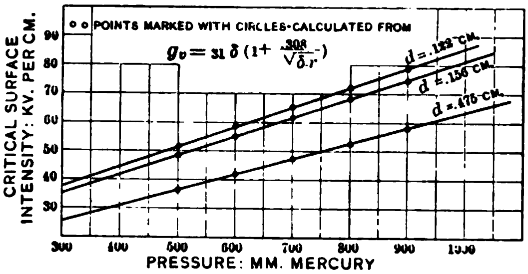

FIG. 5—DATA FOR LINES TAKEN FROM WHITEHEAD'S "ELECTRIC STRENGTH OF AIR, II," FIG. 6.

$$g_v = g_0\,\delta\left(1 + \frac{k}{\phi(f)\sqrt{\delta r}}\right)$$

Investigation of this over a very wide range of frequency will be of great theoretical interest. Direct-current points by Watson are also given on curves (Fig. 6). It is interesting to note that these points do not indicate increased g_v at lower frequencies.

While g_v over the commerical transmission range is not appreciably affected by frequency, it must be remembered that the *power loss over this range, with sufficient accuracy for practical calculation,* increases directly with the frequency, as shown in Part I. It will also be of theoretical interest to investigate this over a very wide range of frequency. The difficulties in making such a comparison even over a short range are many, due to changes in wave shape, power factor, etc.

V. Relation between Spark-Over and Corona for Parallel Wires and Concentric Cylinders

If impressed voltage is gradually increased on two parallel wires placed a considerable distance apart, in air, so that the ratio s/r is above a *certain minimum* value, the first evidence of stress in the air is visual corona. If voltage is still further increased the wires become brighter and the corona has the appearance of extending further out from the surface. Finally, when the voltage has been sufficiently increased, at some chance place, a spark will bridge between the conductors. When the spacing is small, so that s/r has a certain *minimum value*, spark and corona may occur simultaneously, or the spark may bridge across before corona appears. This value of s/r is a critical ratio. If the spacing is still further reduced, so that s/r is below the critical ratio, the first evidence of stress is complete spark-over and corona never appears.

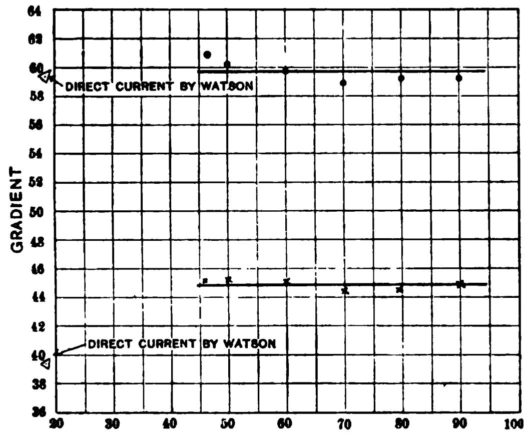

Fig. 6—Variation of Gradient with Frequency.
These curves are plotted to an exaggerated scale to magnify any variations.

A considerable number of tests was made to study spark-over and corona on parallel wires. The conductors in these tests were supported on wooden wheels in a wooden framework as in former tests for visual corona, except that the wires were not allowed to come in contact with the wood at point of support, but rested on aluminum shields spun on a curve over the end wheels. See Fig. 7. This method of support was found necessary, as otherwise spark-over always took place at the ends. The apparatus worked very well except for very large or very small conductors, when it was found almost impossible to support the wires without spark-over at the shields.

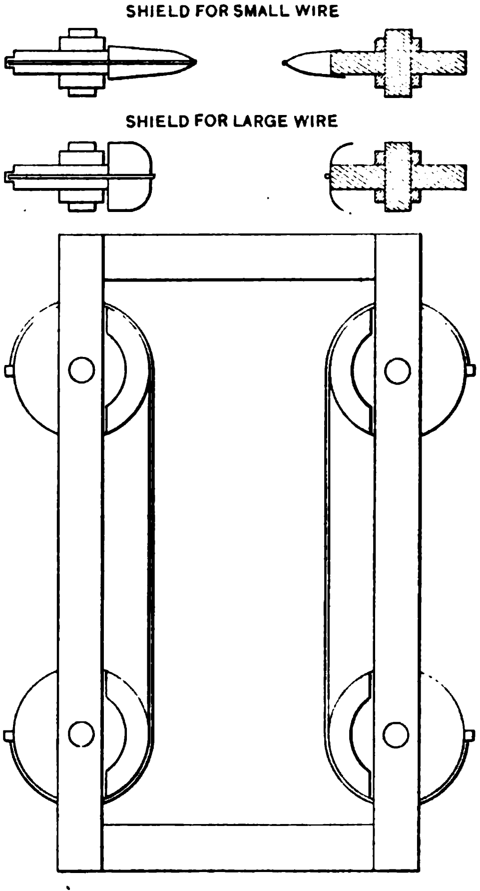

FIG 7

The conductors ranged in size from 0.15 cm. to 1.00 cm. in diameter, and the spacing for spark-over from 1.2 to 30 cm. The temperature was kept nearly constant. The conductors were polished after each test.

The method of test was to start at the smaller spacing with a given value of r and measure the spark-over voltage. The spacing was increased by steps and spark voltage measured. When the spacing was above the critical ratio of s/r, where corona formed before spark-over, the corona voltage was noted first. The voltage was then increased until spark-over occurred. The spark-over point is not as constant or consistent* as the corona point and is susceptible to change with the slightest dirt spot on the conductor surface, and any unsteady condition in the circuit, etc. At the beginning of the tests it was found necessary, in order to get consistent results, to put water tube resistances in series with the conductors to eliminate resonance. These resistances were high, but not sufficiently so to cause an appreciable drop in voltage before arc-over.

TABLE III

CORONA AND SPARK-OVER FOR PARALLEL WIRES

Test No. 166 No. 0 wire

Values read corrected to 25 deg. cent. and 76 cm. baro.

Spacing	Effective kv. to neutral		Maximum values			
Cm. S	Corona e_v	Spark e_s	Corona e_v	Spark e_s	Corona g_v	Spark g_s
2.54	None	15.8	—	21.9	—	41.4
3.81	*	22.5	—	31.2	—	42.5
5.08	*	27.3	—	37.9	—	43.2
6.35	*	31.05	—	43.2	—	43.8
7.62	*	35.0	—	48.5	—	44.9
8.89	*	37.35	—	51.8	—	45.0
10.16	40.4	40.9	56	56.7	44	44.6
12.70	41.8	42.1	58	58.1	44	44.1
13.97	43.7	46	63.7	60.5	44.2	46.7
15.24	45.9	48.1	63.6	67	45.1	48.9
15.78	46.6	54.1	64.8	75	43.8	50.8
20.32	48.9	59.6	67.7	82.8	44	53.7
22.86	50.1	66.2	69.7	91.7	43.7	56.8
25.40	51.1	71.5	70.7	99.2	43.1	60.4
27.94	52.1	79	72.4	109.7	42.9	65.1
30.48	53.1	84.5	74	117	42.9	67.9
33.02	54.1	89.6	74.8	124	42.4	70.2
35.56	55.1	95.5	76.5	132.5	42.6	73.9
38.10	56.1	102.3	77.8	141.9	42.7	77.8
40.64	57.1	106.5	79.4	149	42.9	80.5
60.96	63.3	—	87	—	42.9	—

Temperature 17 deg. cent. Bar. 75.3 cm.

Wire No. 0. Diameter 0.825 cm.

Table III is a typical data table. Each point is the average of a number of readings.

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* Above the critical ratio of s/r, or where corona forms first.

In columns 4 and 5 are voltages reduced to maximum value to neutral and corrected to standard δ. Column 6 gives the surface gradient for corona while column 7 gives surface gradient for spark

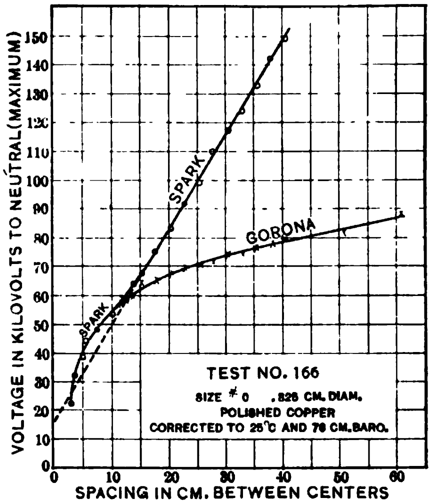

FIG. 8A—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES.

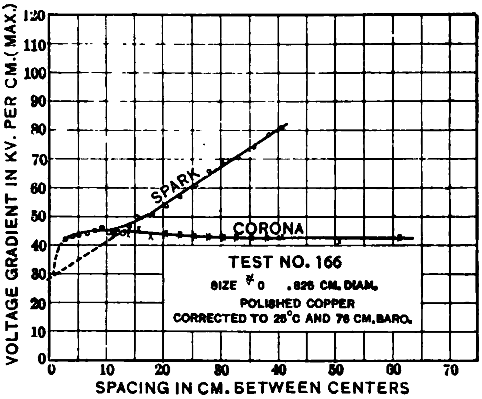

FIG. 8B—SPARK AND VISUAL CORONA VOLTAGE GRADIENTS FOR PARALLEL WIRES.

up to the spacing where corona starts first; above this critical spacing it is the ***apparent surface gradient***, as the conductor above this point must be larger on account of corona. As the field around the conductors at the small spacings is very much distorted it is necessary to use the following rather complicated formulas to calculate the surface gradient.

$$g = \frac{e}{\frac{D\,r}{p} \log_e \frac{p + D}{p - D}}$$

where

$$D = \frac{s - 2\,r}{2}$$

s = distance between conductor centers.
r = conductor radius.

$$p = D \sqrt{1 + \frac{2\,r}{D}}$$

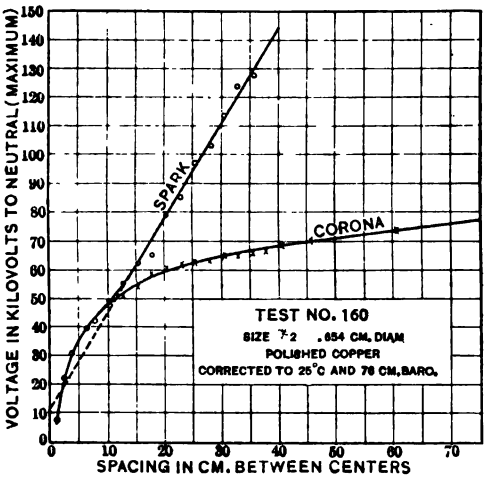

FIG. 9A—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES

Fig. 8A is a typical curve. Voltage is plotted with spacing for spark and corona. Up to spacing 12.4 cm. there is spark-over before corona. This curve seems to be continuous with the corona curve which starts at this point. The spark curve here branches* and is very close to a straight line within the voltage range. In Fig. 8B the surface gradient curves are plotted. The corona gradient is a straight line parallel to the X axis, with a slight hump at the critical ratio of s/r. The apparent spark gradient is also a straight line, within the test range. It intersects the corona line at the critical ratio point, or at

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*The spark curve above the triangular paint, where corona is present, is affected by relative humidity to some extent, the voltage increasing with increasing humidity. Values given are for fairly low humidity or dry air.

what may be termed the triangular point, and extended cuts the g axis at $g = 30$. Figs. 9 to 12 give similar curves for different sizes of wire. For a given spacing the spark-over voltage increases as the size of the conductor decreases.

It is important to note that for all sizes of wire the spark gradient curve extended as a straight line cuts the gradient axis at $g = 30$. That is, at zero spacing, where, compared with the distance apart, the conductors are plane surfaces, the gradient has the same numerical value as the *disruptive gradient* g_0. This seems to be a further check on g_0. Spark curves extended as straight lines through the critical ratio point and intersecting the gradient axis at $g = 30$ are shown in Fig. 13. The triangular point or critical ratio of s/r is tabulated in Table IV.

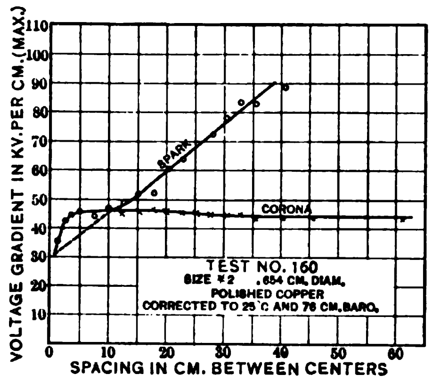

FIG. 9B—SPARK AND VISUAL CORONA VOLTAGE GRADIENTS FOR PARALLEL WIRES.

TABLE IV

CRITICAL RATIOS s/r—EXPERIMENTAL VALUES

Size—B. & S.	Radius cond. cm.	s cm.	S/r
0	0.461	13.5	29.3
0	0.412	11.7	28.4
2	0.327	10.2	31.2
4	0.260	7.9	30.4
5	0.230	7.3	31.7
6	0.205	6.2	30.2
8	0.162	4.8	29.6
10	0.129	4.0	31.0
12	0.103	3	29.1
			Average 30.1

Intersection point of g_v and g_s.

Its average value is $s/r = 30$. If we assume that the spark gradient curve is a straight line, the conditions are that it must cut the corona gradient line at $s/r = 30$ and extended must cut the g axis at $g_0 = 30$. The equation for g_v is

$$g_v = 30\left(1 + \frac{0.301}{\sqrt{r}}\right) \tag{6a}$$

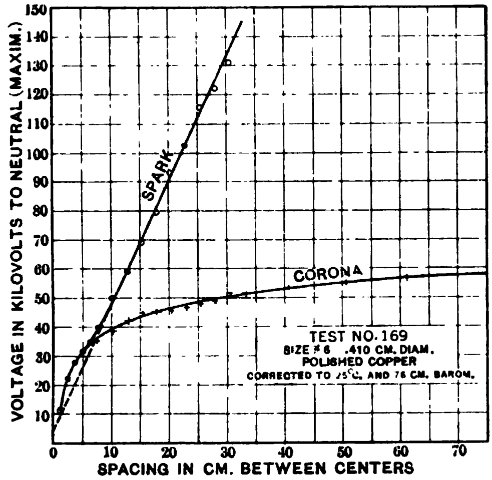

FIG. 10A—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES

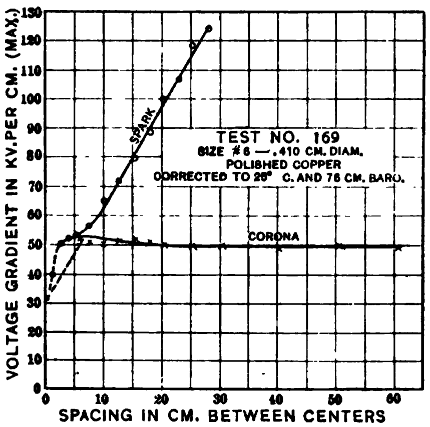

FIG. 10B—SPARK AND VISUAL CORONA VOLTAGE GRADIENTS FOR PARALLEL WIRES.

Therefore

$$g_s = g_0\left(1 + \frac{0.301}{\sqrt{r}}\,\frac{s}{r}\,\frac{1}{30}\right)$$

$$= 30\left(1 \times \frac{0.01}{\sqrt{r}}\,\frac{s}{r}\right) \text{kv. per cm. max.}$$

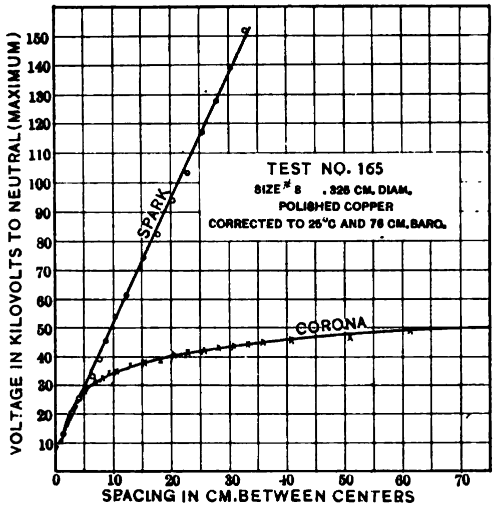

FIG 11A—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES.

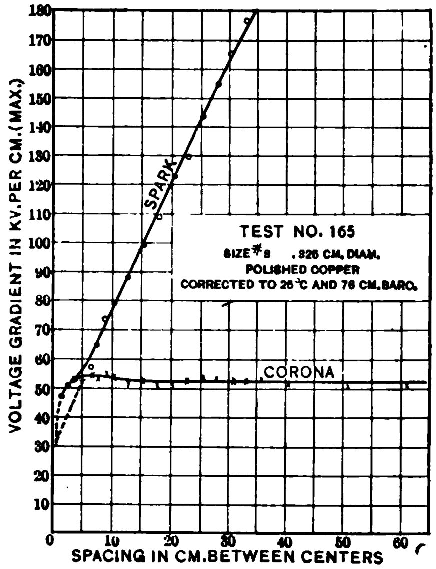

FIG. 11B—SPARK AND VISUAL CORONA VOLTAGE GRADIENTS FOR PARALLEL WIRES.

At $s/r = 30$, g_s reduces to g_v and formula (5*a*) should be used

$$e_s = g_s\, r \log s/r \text{ kv. max. to neutral,}$$

or more accurately,

$$e_s = g_s \frac{r \log s/r}{1 + \dfrac{2r}{s - 2r}}$$

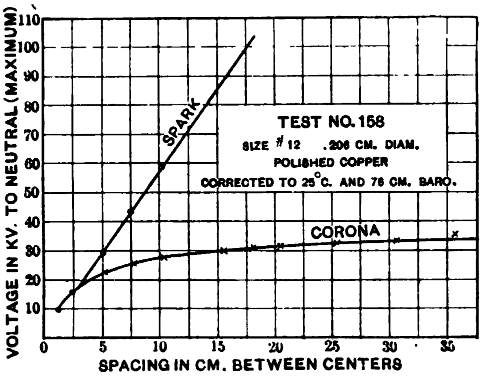

Fig. 12a—Spark and Visual Corona Voltages for Parallel Wires.

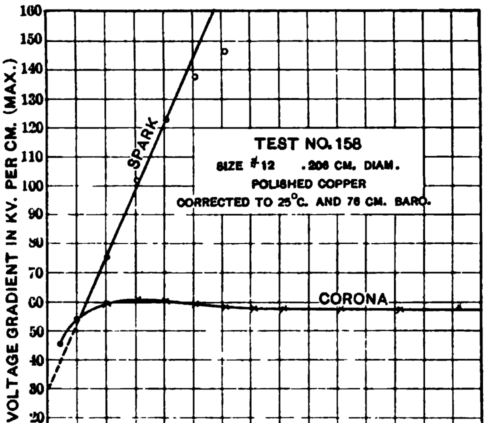

Fig. 12b—Spark and Visual Corona Voltage Gradients for Parallel Wires.

In Fig. 13 each drawn curve is for g_s values calculated for varying spacing at constant radius. The points are measured values. The corona boundary line is the g_v curve; it intersects the g_s curves at $s/r = 30$. Corona does not form below this line, but spark jumps across immediately.

In Fig. 14 each curve is drawn for a constant spacing and varying radius. The broken line is the critical ratio line; it also corresponds to the g_v curve. For spacing below this line spark takes place immediately before corona forms, and the g_s values fall pretty well on the g_v line, as shown by triangles. They generally fall a little low.

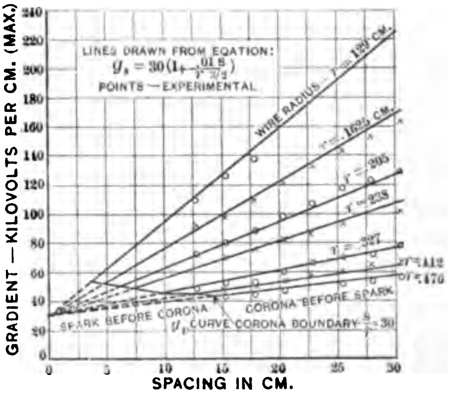

FIG. 13—SPARK-OVER GRADIENTS FOR PARALLEL WIRES.

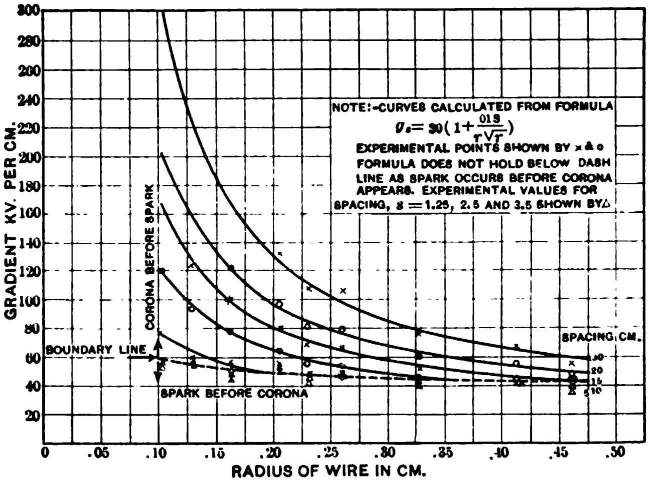

FIG. 14—RELATION BETWEEN SPARK-OVER GRADIENT AND RADIUS OF WIRE FOR SPARK BETWEEN PARALLEL WIRES.

Fig. 15 is voltage plotted in the same way. Below the corona boundary where spark occurs before corona, the e_s curve does not hold. The broken lines are calculated from g_v and e_v.

The points are observed values. Thus corona gradient and spark-over gradient and hence spark voltage and corona voltage, below $s/r = 30$, are the same.

In Fig. 16 the drawn lines are calculated from

$$e_s' = 3.4\, s + \frac{s + 5}{2.5 \sqrt{r}} \text{ maximum kv. to neutral}$$

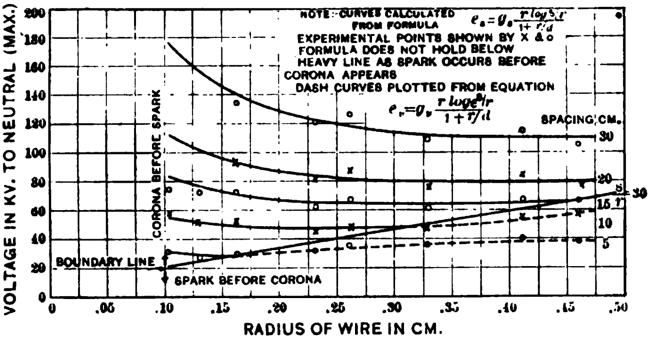

FIG. 15—RELATION BETWEEN VOLTAGE AND RADIUS OF WIRE FOR SPARK BETWEEN PARALLEL WIRES.

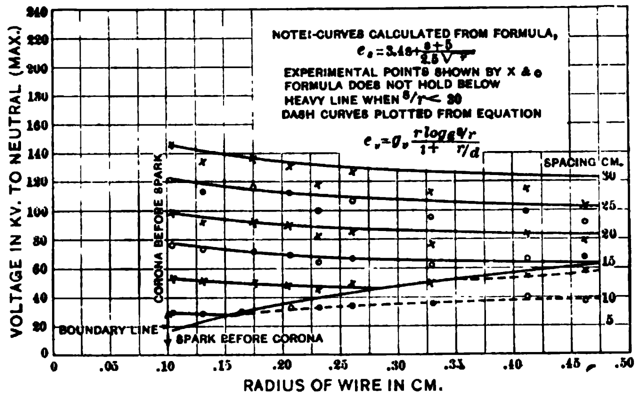

FIG. 16—RELATION BETWEEN VOLTAGE AND RADIUS OF WIRE FOR SPARK BETWEEN PARALLEL WIRES.

This formula is based on the assumption that all sizes of wire for a given spacing would spark over at the same voltage if there were no "corona resistance."

For no "corona resistance," spark would take place where $s/x = 30$, where x is the diameter of conductor and corona, and g_0 at $x = 30$ kv. per cm.—that is, $3.4\, s$.

However, as small wires require higher voltage than larger ones there is a " drop " due to corona resistance which is a function of r. From experiments

$$e_d = \frac{s + 5}{2.5 \sqrt{r}}$$

Hence total spark-over voltage is

$$e_s' = 3.4\, s + \frac{s + 5}{2.5 \sqrt{r}}$$

The measured points do not follow this formula as well as the one based on a straight line gradient. The method of derivation, however, is interesting.

The reason that spark takes place before corona can form, at small spacing or below $s/r = K$, can be seen as follows:

Considering first a wire in the center of a cylinder,

$$g_v = \frac{e_v}{r \log_\epsilon R/r}$$

$$e = g_v\, r \log_\epsilon R/r$$

Assuming g and R constant, increasing r increases e up to a certain maximum point where e begins to decrease. Thus beyond the maximum value of e the effect of reducing the flux density by increasing r is overcome by decreasing the distance between cylinders or reducing the ratio R/r. If corona could form where R/r = ratio for maximum e, or less than for maximum e, the conductor would be, in effect, increased in radius by the conducting corona. This new radius would require lower e for corona, hence represents an unstable condition —that is, spark-over. Thus corona will appear before spark where R/r is greater than K, and spark must take place and corona cannot form where R/r is less than K. Under the above assumption of constant g the critical ratio is $R/r = \epsilon$. The ratio $R/r = \epsilon$ is generally taken as the ratio for maximum dielectric strength of concentric cylinders. This does not seem correct, as in the above assumption g_v was taken as constant. We know, however, that g_v is a function of r, and for air is:

$$g_v = g_0 \left(1 + \frac{0.301}{\sqrt{r}}\right)$$

$$e = g_0 \left(1 + \frac{0.301}{\sqrt{r}}\right) r \log_\epsilon R/r$$

Differentiating for maximum,

$$\frac{de}{dr} = g_0 \left[\left(1 + \frac{0.301}{2\sqrt{r}}\right) \log_e R/r - 1 - \frac{0.301}{\sqrt{r}} \right]$$

or

e is maximum when

$$\left[\left(1 + \frac{0.301}{2\sqrt{r}}\right) \log_e R/r - 1 - \frac{0.301}{\sqrt{r}} \right] = 0$$

This gives a ratio of R/r greater than ϵ. The experimental ratio in Fig. 17 is 3 and checks with the above.

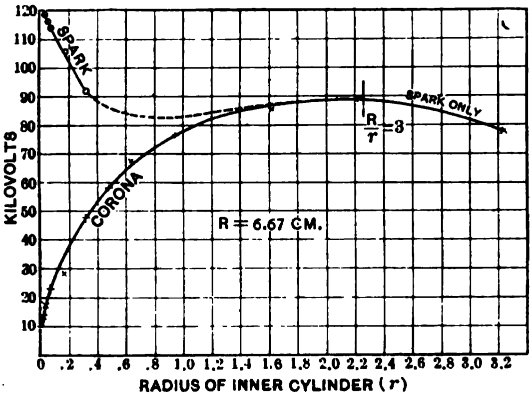

Fig. 17—Relation of Corona and Spark-over for Concentric Cylinders.

If a very small value of r is taken so that corona forms, and the voltage is increased, spark-over finally occurs. It might be supposed that as the voltage is increased and the center wire becomes larger and larger in effect, due to conducting corona, that finally, when R/corona radius = critical ratio, spark-over would occur. This is not the case. It takes a much higher voltage for the small wire plus corona than for metallic cylinders at maximum ratio. Hence corona seems to be either in effect a series resistance, or grades or distributes the flux density. See Fig. 17. This has an important bearing on the study of the power loss equation.

Taking now the exact equation for parallel wires

$$g_v = \frac{e_v}{\frac{D\,r}{p}\log_e\frac{p+D}{p-D}}$$

$$e_v = g_0\left(1 + \frac{0.301}{\sqrt{r}}\right)\frac{D\,r}{p}\log_e\frac{p+D}{p-D}\ .$$

Varying r for constant $s = 10$ it is found that e_v is maximum when $s/r = 6.67$. See Fig. 18. Experiments show this ratio to be 30. The difference is evidently due to the distorted condition of the field at the small spacings.

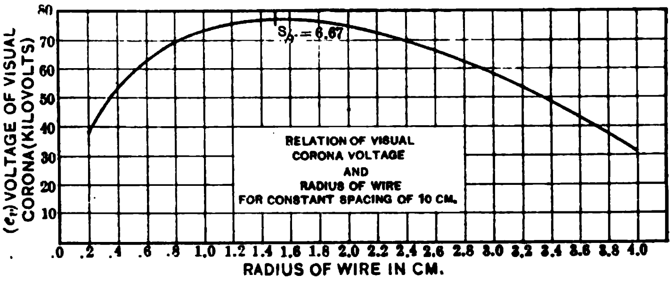

FIG. 18

The visual corona voltages, or the spark-over voltages *below* the critical ratio of s/r or R/r, should be of practical value for voltage measurement on account of the accuracy at which they may be determined or calculated for different temperatures, barometric pressures, etc.

VI. INFLUENCE ON CORONA AND SPARK-OVER OF WATER AND OIL ON THE CONDUCTOR SURFACE

These tests were made in a manner exactly similar to the dry spark-over and corona tests. In the oil tests, the surface of the wire was coated with a thin even film by means of an oiled rag. For the wet tests water was sprayed on the conductor surface after each reading by means of an atomizer. Figs. 19–23 are dry, wet and oil curves for three different sizes of wire.

For spark-over both water and oil have approximately the same

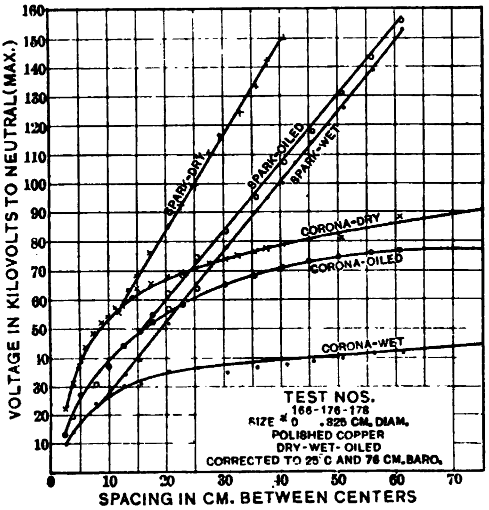

FIG. 19—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES.

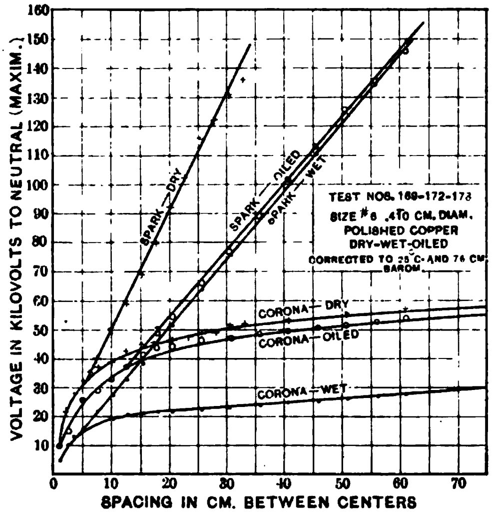

FIG. 20—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES.

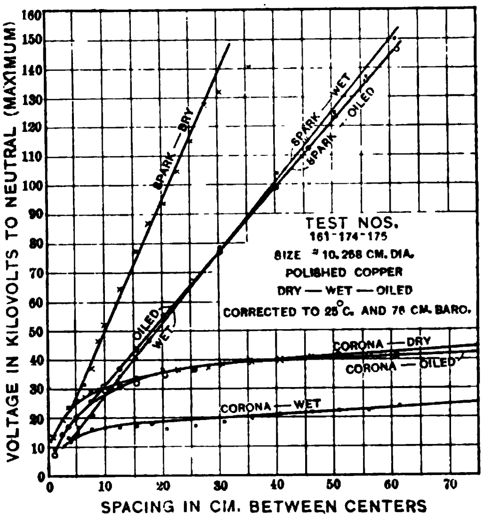

Fig. 21—Spark and Visual Corona Voltages for Parallel Wires.

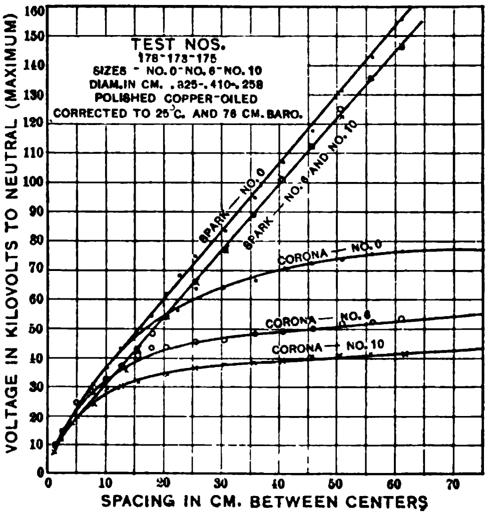

Fig. 22—Spark and Visual Corona Voltages for Parallel Wires.

effect, that is, give very nearly the same spark-over voltage for all sizes of conductor. This curve very closely follows the needle gap curve.

For corona, water very greatly lowers g_v. Oil lowers g_v but to a much less extent than water. Where the conductor is very small the per cent increase in diameter due to oil more than compensates for the lowering effect. The visual corona gradient (max.) for oil- and water-coated conductors may be found thus:

Water surface by fine spray or fog:

$$g_v = 9\left(1 + \frac{0.815}{\sqrt{r}}\right)$$

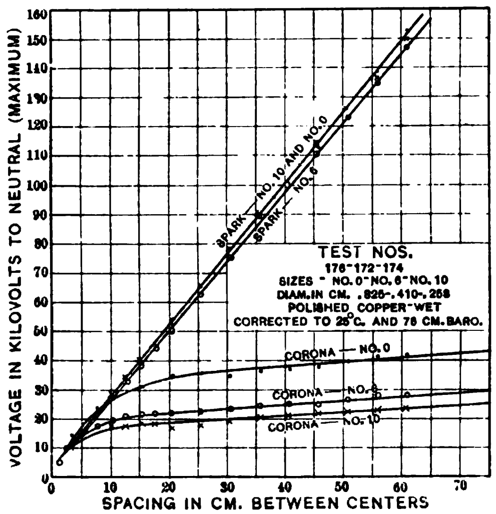

FIG. 23—SPARK AND VISUAL CORONA VOLTAGES FOR PARALLEL WIRES.

Oil film surfaces:

$$g_v = 19\left(1 + \frac{0.65}{\sqrt{r}}\right) \quad \text{See Fig. 24.}$$

VII. SOME ADDITIONAL REMARKS ON DISRUPTIVE GRADIENT—g_0

Fig. 25 shows three entirely different methods which all seem to indicate a constant disruptive gradient of $g_0 = 30$ for air, as follows:

a. *By Visual Corona.*

$$g_v = 30\left(1 + \frac{0.301}{\sqrt{r}}\right)$$

b. *By Power Measurement.* This curve is plotted between the square root of measured power and the surface gradient g. The curve intersects the axis at $g = 30$ or

$$p = m\,(g - g_0)^2 = m\,(g - 30)^2$$

c. *By Spark-Over Between Parallel Wires.* This curve is plotted between gradient and spacing. The curve, extended to zero spacing—where r is so large compared to s, that the wire surface may be considered a plane—intersects the g axis at $g_0 = 30$.

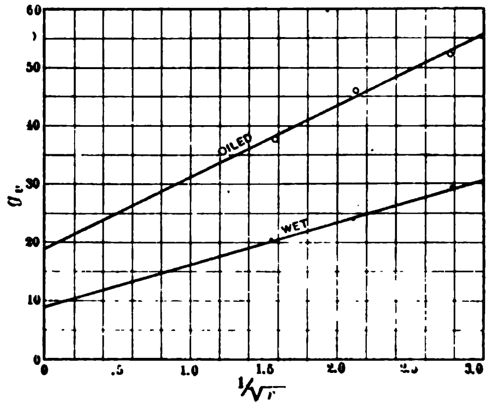

FIG. 24—RELATION OF g_v TO $1/\sqrt{r}$

VIII. RUPTURING ENERGY OF AIR

It is now of theoretical interest to investigate the energy in a zone surrounding the surface of the conductor just at the instant before visual corona, when the outer boundary of the zone is an equigradient circle g_0, and the inner boundary, the conductor surface at gradient g_v.

The tests for visual corona show that the surface gradient, g_v, for the first appearance of visual corona is not constant for all sizes of conductors, but is a function of the radius, r, of the conductors. g_v increases as r decreases. From the equations, when δ = unity

$$g_v = \frac{e_v}{r \log_e s/r}$$

$$g_0 = \frac{e_v}{(r + x) \log_e s/r}$$

It seems that air has a constant breakdown gradient g_0 for given density δ, but that energy is necessary to start rupture.

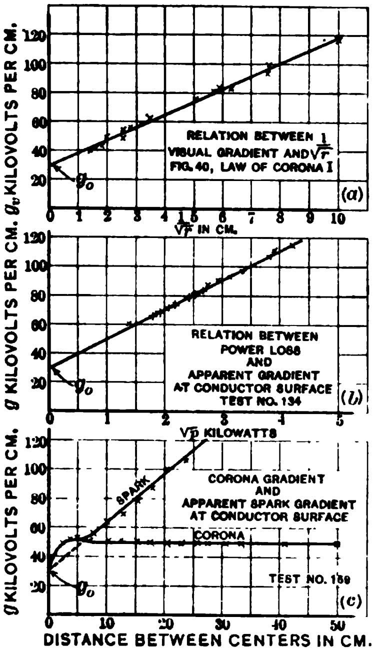

FIG. 25—DIFFERENT METHODS OF OBTAINING g_0.

This means that rupture cannot occur at the surface of the conductor when the surface stress becomes g_0, but only after the gradient reaches a higher value, g_v, at the conductor surface and, hence, g_0, at a finite distance x from the conductor surface when rupture occurs. The energy stored in the zone between g_v and g_0 may hence be called the "rupturing energy."* See Fig. 26.

---

* This must not be confused with the power lost by corona. It is the energy stored between g_v and g_0 to start rupture. or up to the point where loss begins.

The rupturing energy for a conductor of radius r, and one cm. long and $\delta = 1$ may be calculated thus:

$$g_v = \frac{e_v}{r \log_e s/r}$$

From experiments

$$g_0 = \frac{e_v}{(r + \phi\, r) \log_e s/r} = \frac{e_v}{(r + 0.301 \sqrt{r}) \log_e s/r} = 29{,}800$$

Therefore $0.301 \sqrt{r}$ is the thickness of the energy film x, and $(r + 0.301 \sqrt{r})$ is the outer radius of the energy cylinder.

Also

$$e_v = (r + 0.301 \sqrt{r})\, g_0 \log_e s/r$$

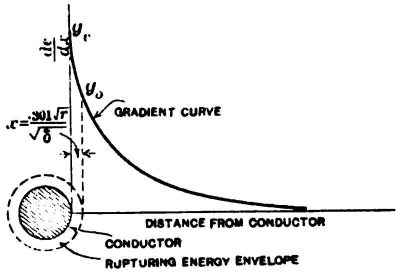

FIG. 26—RUPTURING ENERGY IN AIR SURROUNDING ONE OF TWO PARALLEL CONDUCTORS.

From Fig. 26, rupturing energy is found

$$d\,\omega = \frac{K}{2}\, g^2\, d\,V$$

where $K = 0.08842\ 10^{-12}$ coulombs per volt per cm. thickness of dielectric (air) per square cm. cross-section,

but

$$d\,V = 2\,\pi\, y\, dy$$

therefore

$$d\,\omega = \pi\, K\, g^2\, y\, dy$$

Therefore

$$\omega = \pi K \int_{y = r}^{y = (r + 0.301 \sqrt{r})} g^2\, y\, dy$$

Substituting

$$g = \frac{e_v}{y \log_\epsilon s/r}$$

$$\omega = \frac{\pi K e_v^2}{(\log_\epsilon s/r)^2} \int_{y=r}^{y=(r+0.301\sqrt{r})} \frac{dy}{y}$$

but

$$e_v = (r + 0.301\sqrt{r})\, g_0 \log_\epsilon s/r$$

Therefore

$$\omega = \pi K g_0^2 (r + 0.301 \sqrt{r})^2 \log_\epsilon \frac{r + 0.301 \sqrt{r}}{r}$$

$$\omega = 25 (r + 0.301 \sqrt{r})^2 \log_\epsilon \left(\frac{r + 0.301 \sqrt{r}}{r}\right) 10^{-5} \text{ joules.}$$

ω is the energy in joules that must be stored around the surface of the wire per cm. length of conductor to start corona at $\delta = 1$. It is seen that the rupturing energy increases as r increases. The rupturing energy is independent of s—that is, g_v for a given wire must be independent of s, which is borne out by experiment, and is an interesting point.

From Section III of this paper, on temperature and pressure, it is seen that

$$g_v = g_0 \delta \left(1 + \frac{k}{\sqrt{r \delta}}\right)$$

This apparently means that the disruptive gradient g_0 varies directly with the air density δ. Also that the energy storage distance x increases, as δ and g_0 decrease.

$$x = \frac{0.301 \sqrt{r}}{\sqrt{\delta}}$$

Then

$$g_0 \delta = \frac{e_v}{\left(r + \frac{0.301 \sqrt{r}}{\sqrt{\delta}}\right) \log_\epsilon s/r}$$

Introducing δ into the energy equation,

$$\omega = 25\left(r + \frac{0.301\sqrt{r}}{\sqrt{\delta}}\right)^2 \log \frac{r + \dfrac{0.301\sqrt{r}}{\sqrt{\delta}}}{r}\, 10^{-5} \text{ joules per cm. conductor.}$$

In Fig. 27 the "rupturing energy" calculated from the above is plotted for different conductor radii and at $\delta = 1$ to show the energy increase with increasing r.

In Fig. 28 the "rupturing energy" for a given size conductor is plotted with δ. This curve shows that energy to start rupture increases almost directly with the air density.

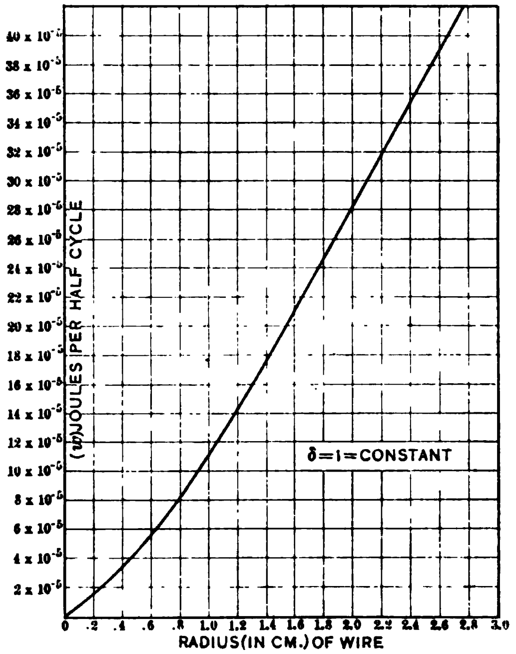

FIG. 27—RELATION BETWEEN RUPTURING ENERGY AND RADIUS OF WIRE.

IX. SOME REMARKS ON POWER LOSS BY CORONA

The equation for power loss by corona on parallel wires is

$$p = K'/\delta\, f \sqrt{r/s}\,(e - g_0\, m\, r\, \delta \log s/r)^2 \times 10^{-5} \qquad (6)$$

At $\delta = 1$ and $m_0 = 1$,

$$p = K' f \sqrt{r/s}\,(e - e_0)^2 \times 10^{-5} \qquad (6')$$

For a wire with a given radius r and ***uniform dielectric flux distribution*** it would be expected that the loss for a given apparent surface gradient, g, would be the same, independent of s, or

$$p = K'' \phi (r) f (g - g_0)^2$$

Equation (6′) may be written

$$p = K' f \sqrt{r/s} (\log s/r)^2 r^2 (g - g_0)^2 \times 10^{-6}$$

Thus for a ***uniform field*** the terms $\sqrt{r/s} (\log s/r)^2$ should cancel and the equations become

$$p = K' f r^2 (g - g_0)^2$$

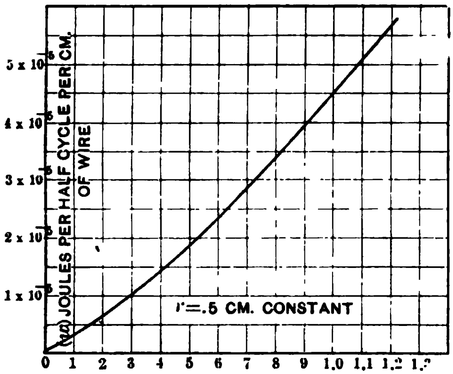

FIG. 28—VARIATION OF RUPTURING ENERGY WITH AIR DENSITY

Fig. 29 shows measured curves plotted between g and $\sqrt{p}$ for a given wire at three different spacings. These curves all intersect the axis at g_0 max. = 30, at $\delta = 1$. s enters as a function, otherwise all of the points would be on the same line. Hence, for parallel wires, when corona starts it acts somewhat as a flexible conductor in which the radius of curvature can change. The slightly non-uniform field, even with large values of s/r, starts distortion, and the effect is accumulative. For a given value of g the loss should therefore be greater at small s than large s. Experiments show this to be the case.

The equation derived for the average spacing is

$$p = 500 f r^2 (g - g_0)^2 \times 10^{-6}$$

$$g = \text{effective gradient } g_0 = 21.2$$

This should probably be the form of the equation for loss in concentric cylinders. For parallel wires it gives values too high at the larger and too low at the smaller values of s/r. The error for parallel wires, neglecting $\phi(s)$, is usually below 20 per cent.

This effect of spacing is brought up here as an interesting point in the complication of the mechanism of corona loss and one of the almost innumerable influences that must be considered in rationalization. Another point of considerable interest is the loss per cycle over a greater frequency range.

X. Stroboscopic Study of Corona

A study of the power loss equation leads one to suspect that the mechanism of corona loss is more complicated than might at first be supposed. This is also indicated by many peculiar phenomena* of the spark discharge. For instance, while investigating a-c. spark-over and corona for parallel wires it was observed that when the end shields are not used, and the wires come directly in contact with the wooden wheel supports, corona often appears to bridge completely between the conductors without dynamic arc. In this case it seemed possible that the corona on, say, the positive wire, extended out further than the corona on the negative wire, then as each wire is alternately positive and negative, the positive discharges overlap and combine in the eye,

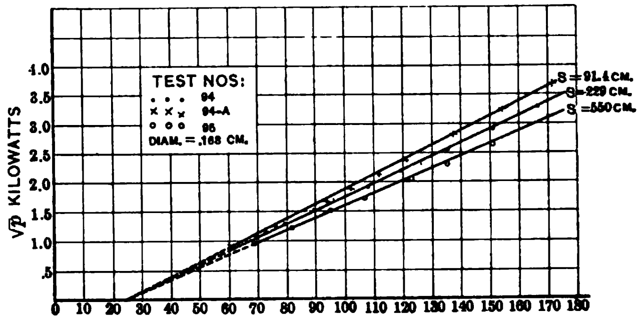

Fig. 29—Relation between Power Loss and Apparent Surface Gradient.

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*An interesting one observed by Mr. C. W. Stone is that in the automobile spark plug, it makes considerable difference, in firing, which polarity is connected to the pointed electrode. Best results are obtained when the negative is connected to the point, indicating a hot negative.

(1) Without stroboscope

Left + (2) With stroboscope Right −

FIG. 30—CORONA BETWEEN COPPER NEEDLE POINTS—25.4 CM. GAP—90,000 VOLTS

PLATE LIII
A. I. E. E.
VOL. XXXI, 1912

[PEEK]

(1) Without stroboscope—72,000 volts.

[PEEK]

Left — (2) With stroboscope—72,000 volts. Right +

[PEEK]

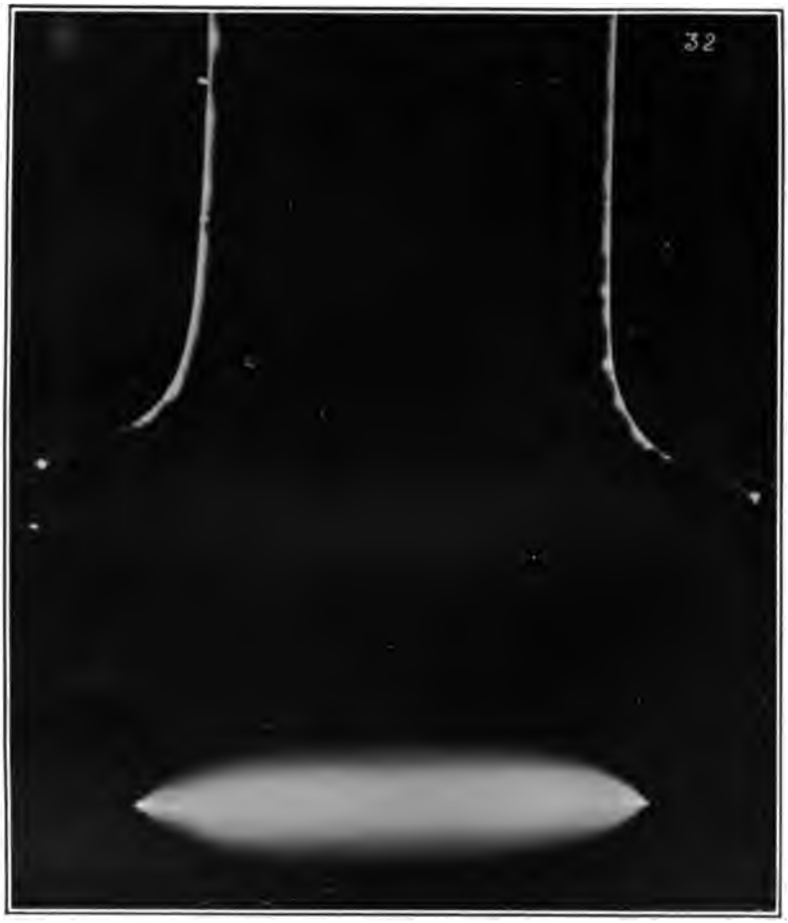
Left + (3) Stroboscope rotated 180 deg. Right —

[PEEK

Left + (4) Same as (3) with voltage increased to 84,000 Right —

FIG. 31—CORONA BETWEEN COPPER NEEDLE POINTS.

Spacing 20.5 cm.



[PEEK]

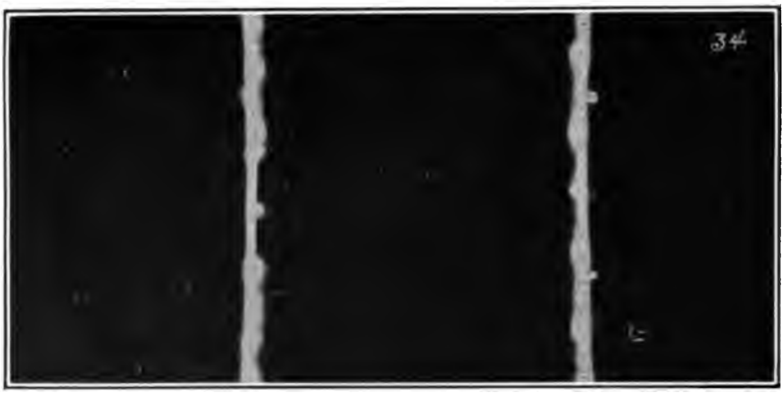
FIG. 32—COMPARISON OF CORONA ON WIRES AND BETWEEN NEEDLES, WITHOUT STROBOSCOPE.

Phosphor bronze wire, spacing 14.5 cm. Spacing of needles 18 cm. 71,000 volts.

[PEEK]

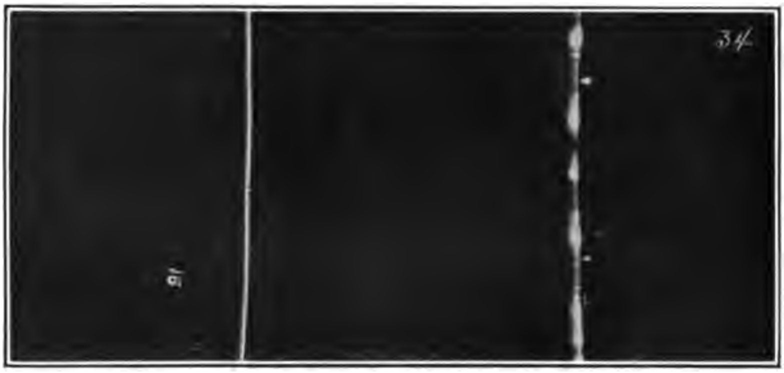
Left — Right +

FIG. 33—COMPARISON OF CORONA ON WIRES AND BETWEEN NEEDLES, WITH STROBOSCOPE.



[PEEK]

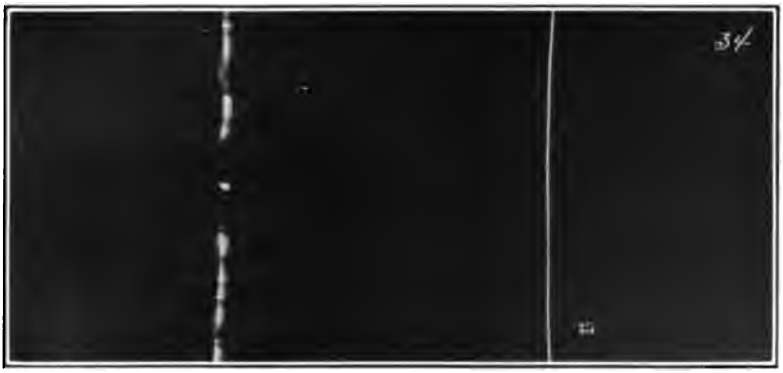
(1) Without stroboscope.



[PEEK]

Left + Right —

(2) With stroboscope.



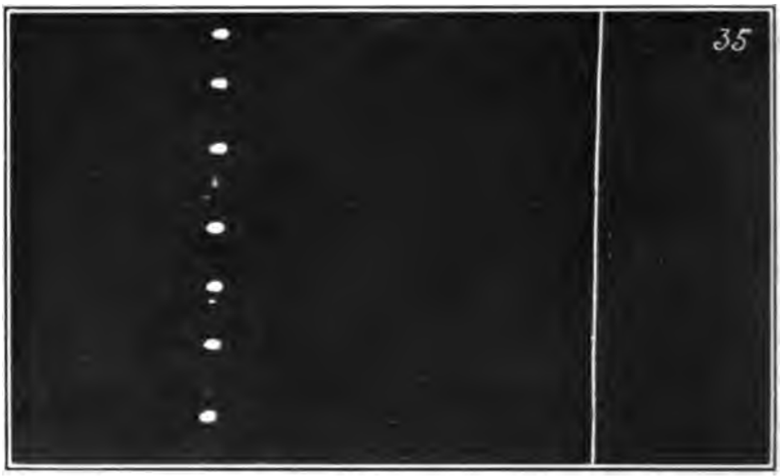
[PEEK]

Left — Right +

(3) With stroboscope rotated 180 deg.

FIG. 34—CORONA ON PARALLEL WIRES.

No. 13 B. & S. wire—spacing 12.7 cm.—82,000 volts.



[PEEK]

Left –   (1)   Right +

[PEEK]

Left +   (2)   Right –

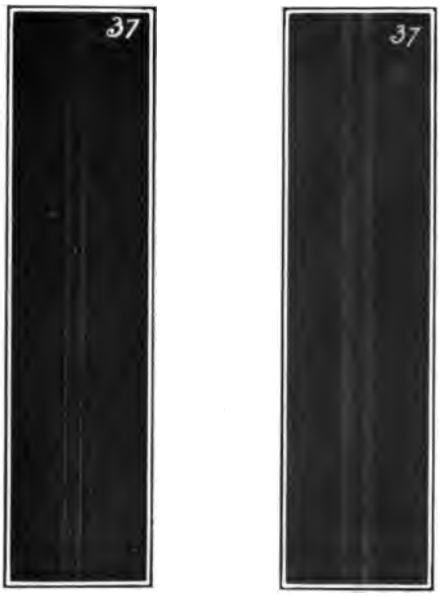
FIG. 35—CORONA ON PARALLEL WIRES.

Iron—first polished and then run at 120,000 volts for two hours to develop spots. With stroboscope. Photographs taken at 80,000 volts. Diameter 0.168 cm. Spacing 12.7 cm.

[PEEK]

FIG. 36—SECTION OF WIRE.

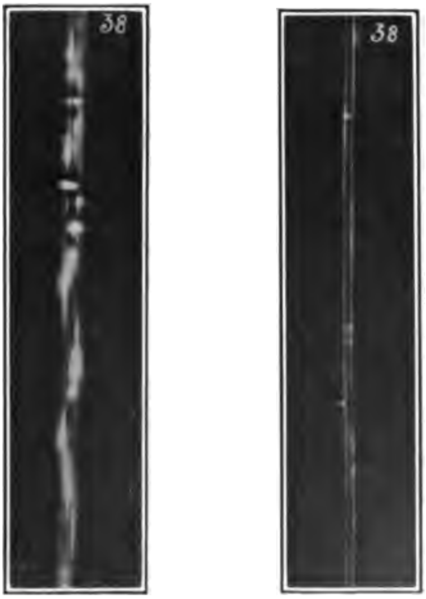
No volts. Bright spots show position of negative "beads"—enlarged scale.



Left + [PEEK] Right − [PEEK]

FIG. 37—POLISHED BRASS ROD.

Diameter 4.75 cm.—spacing 120 cm.—150,000 volts. Note that negative "beads" are just starting to form.



Left − [PEEK] Right + [PEEK]

FIG. 38—COPPER WIRE.

Diameter 0.26 cm.—spacing 120 cm.—200,000 volts. Polished at start—note negative apparently following helical "grain" of wire.

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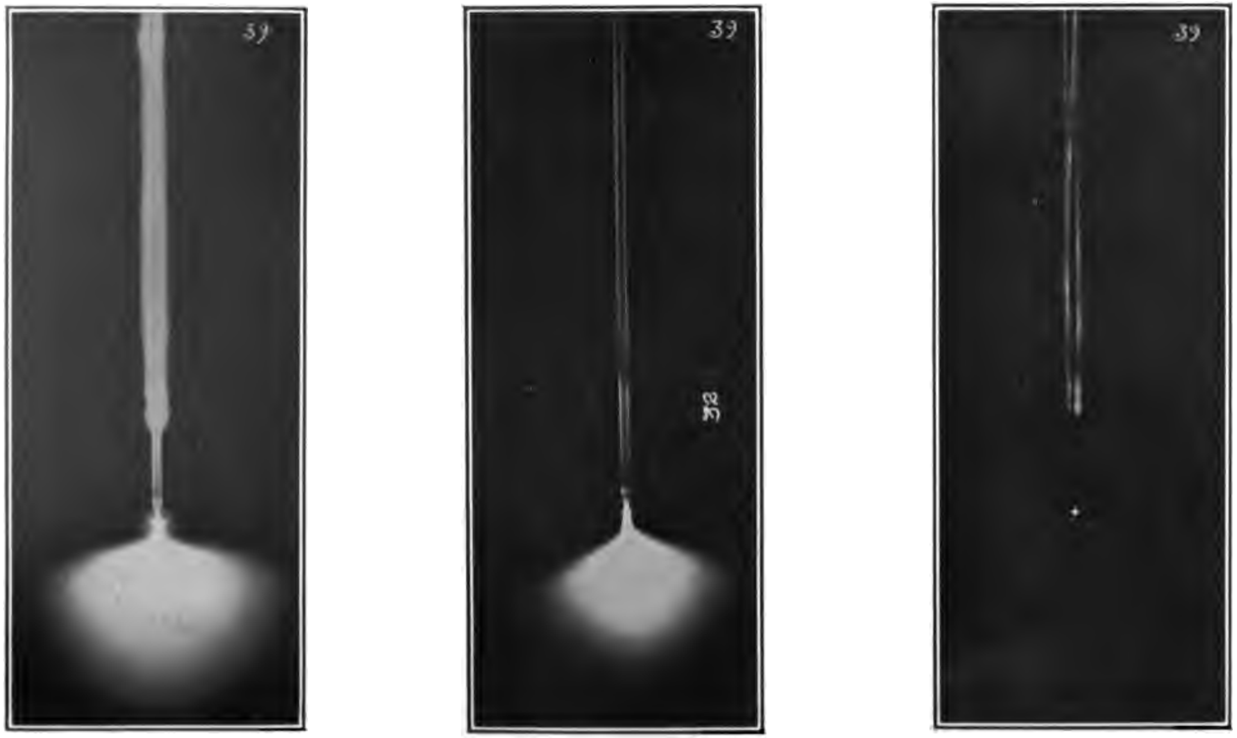


[PEEK]
(1) Without stroboscope.

[PEEK]
(2) With stroboscope—Pos.

[PEEK]
(3) With stroboscope—Neg.

FIG. 39—ONE OF TWO POLISHED STEEL RODS POINTED AT ENDS.

Diameter 0.325 cm.—spacing 120 cm.—180,000 volts.

[PEEK]

FIG. 40—ONE OF TWO PARALLEL STEEL RODS POINTED AT ENDS (DIRTY).

Without stroboscope.

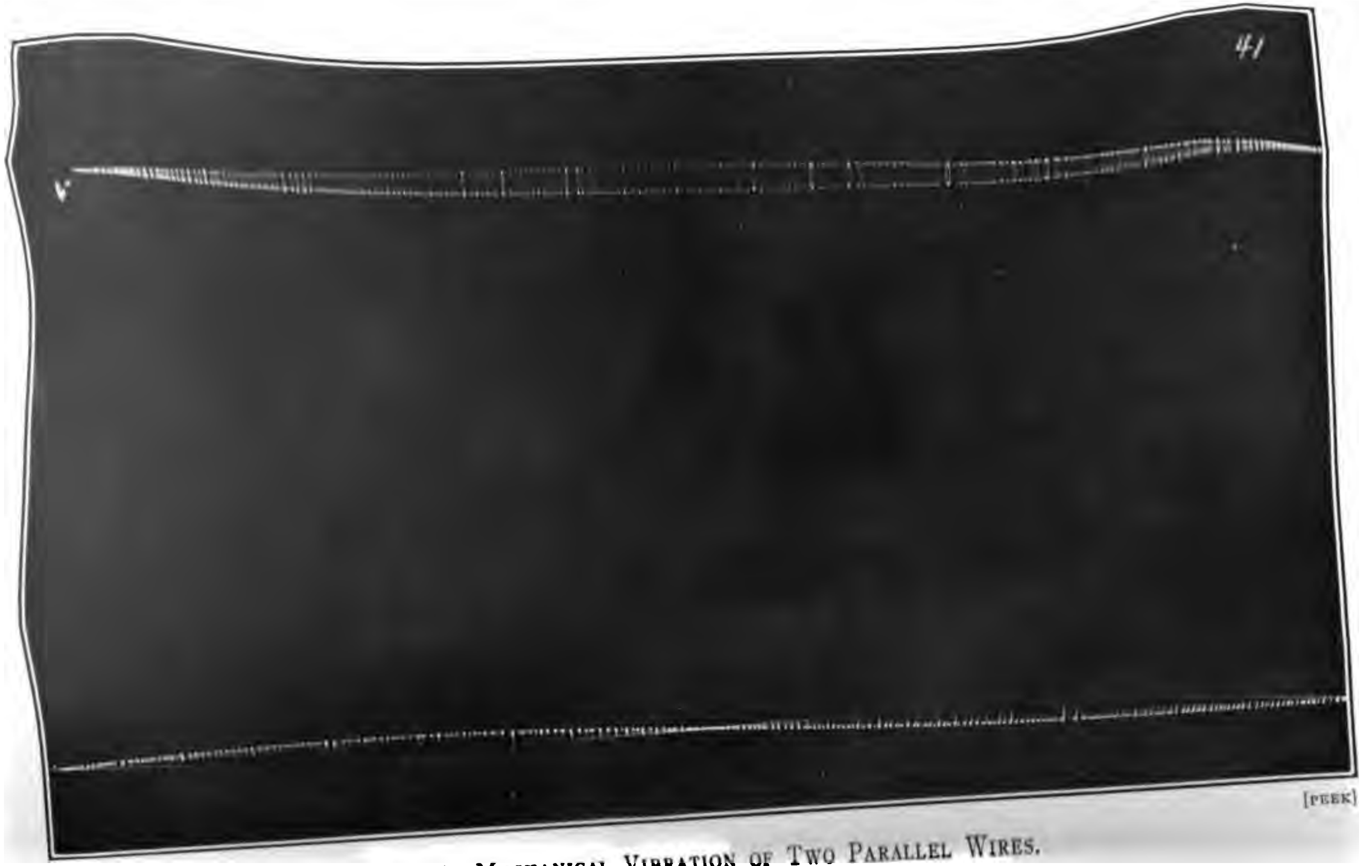


FIG. 41—MECHANICAL VIBRATION OF TWO PARALLEL WIRES.
Length 147 cm.—spacing 49 cm.—diameter 0.00254 cm.—150,000 volts

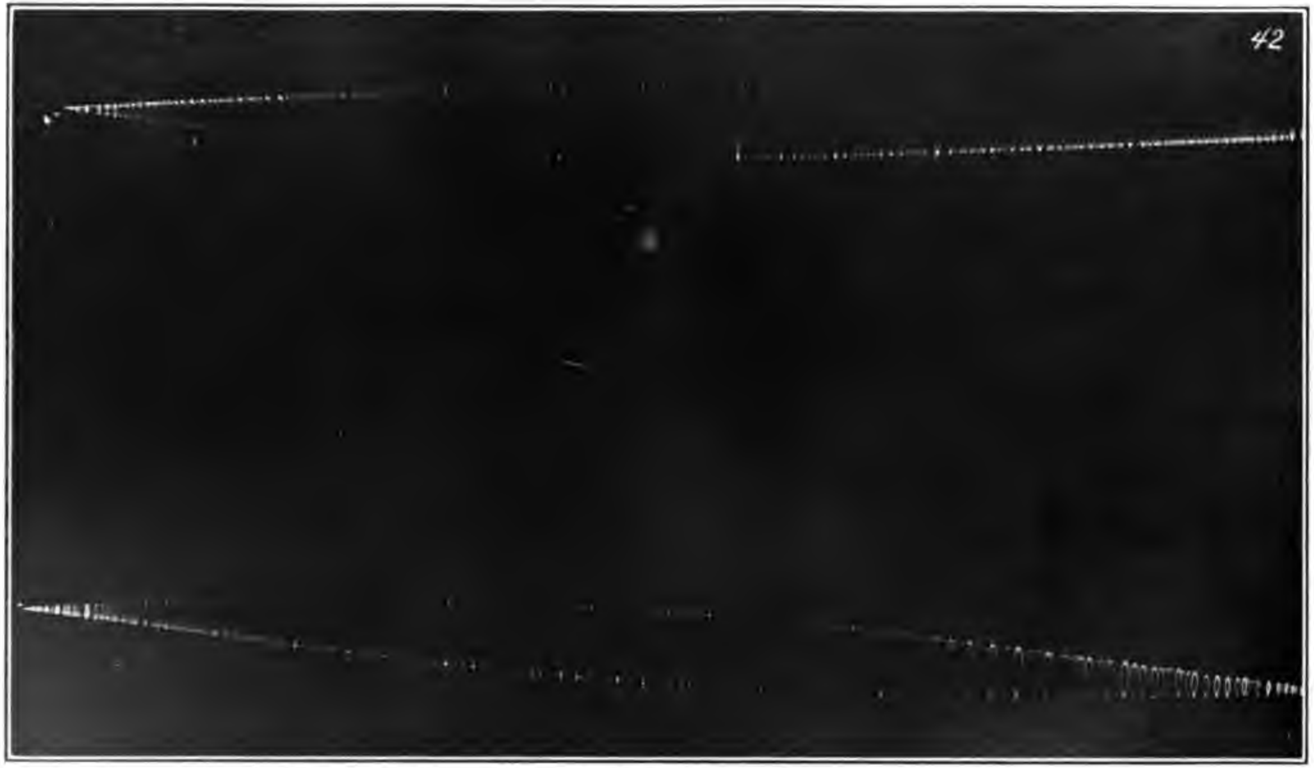
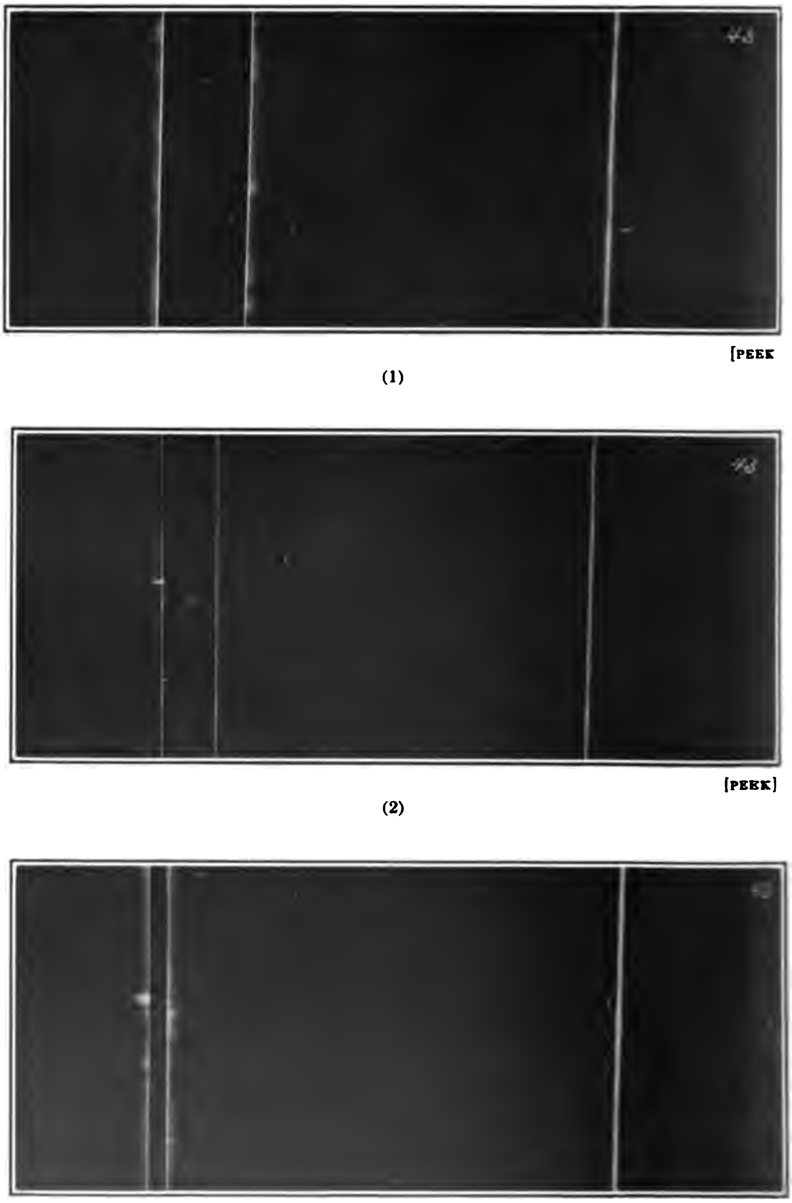


FIG. 42—MECHANICAL VIBRATION OF PARALLEL WIRES. [PEEK]



[PEEK

(1)

[PEEK]

(2)

[PEEK

(3)

FIG. 43—PARALLEL WIRES AT SAME POTENTIAL, WITH DIFFERENT SPACINGS.

At left, view perpendicular to plane of wires.
At right, view in plane of wires.

giving the effect of a single discharge completely across between the conductors.

In the hope of throwing further light on the discharge and loss mechanism an investigation of corona and spark was started with the help of the stroboscope. This investigation is being continued.

A needle gap was first arranged across the transformer with a high steadying resistance. The impressed voltage was adjusted until corona *appeared* all the way between the conductors as in Fig. 30 (1).

Examination of this was then made through the stroboscope, which was so set that the left needle, Fig. 30 (2), was seen as positive, and the right as negative. To the eye, the discharge from the positive needle has a bluish white color and extends out a considerable distance, the negative appears as a red and hot point. This confirms the speculation made above. Thus, the discharge always starts out from the positive toward the negative. Fig. 31 (1) is the discharge as it appears without stroboscope, 31 (2) with right needle as positive, 31 (3) with stroboscope shifted 180 deg. to show left needle as positive. In 31 (4) the stroboscope has the same position as 31 (3), but the voltage is higher, and many fine " static " sparks can be seen. Note that the discharge gives one the impression of a spray issuing from the positive under pressure and being collected in at the negative.

If voltage above the visual corona point is impressed on two parallel polished wires a more or less even glow appears around the wires. After a time the wires have a beaded appearance. On closer examination the beads appear as reddish tufts, while in between them appears a fine bluish white needle-like fringe. On examination through the stroboscope it can be seen that the more or less evenly spaced beads are on the negative wire, while the positive wire has the appearance, if not roughened by points, of a smooth bluish white glow. At points the positive discharge extends out at a great distance in the form of needles; it is probable that it always extends out but is not always visible except as surface glow. Thus, the appearance of beads and fringe to the unaided eye is really a combination of positive and negative corona. In Figs. 32 and 33 two wires are placed close together at the top. The bottom is bent out and needles fastened on. Fig. 32 is without stroboscope. Fig. 33 is taken with stroboscope set to show positive right and negative left. Thus, positive and negative coronas for points and wires are directly compared. Fig. 34 (1) is taken without the stroboscope, (2) with right negative, (3) with stroboscope shifted 180 electrical degrees to show the right positive. Fig. 35 (1) shows the left wire negative and right positive. These wires were, at the start, highly polished. At first corona appeared quite uniform, but after a time under voltage the reddish negative tufts separated, more or less evenly spaced as shown. 35 (2) is the same with stroboscope shifted 180 degrees. Fig. 36 shows a section of this wire photographed on an enlarged scale without voltage. The bright spots are still polished and correspond in position to the negative tufts. The space in between is oxidized. Thus, the negative discharge appears to throw metal or oxide from the surface at discharge points. This takes place with either copper or iron wire.

Fig. 37 shows positive and negative wires widely spaced to get uniform field. A close examination of the negative shows beads about to form. Fig. 38 shows a similar pair of conductors. The negative in this case has formed a helix, apparently following the grain twist of the conductor.

A large fan-like bluish discharge is often observed extending several inches from the ends of transformer bushings, points on wires, etc. This discharge has the appearance of a bluish spray, reddish at the point. The stroboscope shows that the bluish spray is positive, while the red point at the base of the spray is negative. Fig. 39 shows one of two parallel polished rods, (120 cm. spacing), supported at the top and brought to sharp points at the bottom. 39 (1) shows how each wire appears without stroboscope. 39 (2) is the wire when positive; 39 (3) the wire when negative. Note the dark space on 39 (3) between the point and negative corona helix of tufts. 39 (1) shows this space to have only the positive glow.

Water was placed on a pair of parallel conductors. At the wet places the positive corona extended out in long fine bluish-white streamers. See Fig. 40, without stroboscope. With certain forms of dirt on the wires the negative corona appears as red spots, the positive always as streamers. It is also interesting to note that if a uniformly rough wire is taken, as a galvanized wire or "weathered" wire, the positive appears as bluish needles, while the reddish negative is more uniform than on the "corona spotted" polished wire, in which case the negative corona appears as concentrated at the non-oxidized spots. It is probable that the polished spots are kept so by metal and oxide being " thrown out" at the negative, as suggested above.

The stroboscopic study *suggests* that the corona loss is, in effect, in the form of a " conduction " across from positive to negative, always starting from the positive conductor—thus starting alternately at each half cycle, first from one conductor, then from the other. The voltage point on the wave at which corona starts is higher than where it stops. Work is now being done to determine the relative position on wave at start of positive and negative coronas.

Many of the stroboscope data to date are given here as taken and without speculation. It is hoped that considerable light will be thrown on the mechanism of discharge and loss by this investigation.

XI. MECHANICAL VIBRATION OF CONDUCTORS AND OTHER PHENOMENA

Over a year ago a pair of 20-mil steel conductors, 500 feet long, were strung at about 10 ft. spacing, for power loss measurements. It was noticed at high voltage that the conductors vibrated, starting with a hardly perceptible movement, which in a few minutes had an amplitude of several feet at the center of the span. Generally one wire vibrated as fundamental, the other as third harmonic. The period of the fundamental in this case was about one per second.

Figs. 41 and 42 show this condition repeated in the laboratory on short lengths of conductor. In Fig. 41, one wire is vibrating as the fundamental, the other as the second harmonic. The motion is rotary. For the wire with node in center, Fig. 41, it is extremely interesting to note that for about one-half of the rotation the wire appears very bright, for the other half rotation the wire is much less bright. This seems to mean that each part of the wire is rotating at the power supply frequency—60 cycles per second. Hence it has the effect of the stroboscope, and for part of the rotation there is always negative corona and for the other part always positive corona.

Fig. 43 shows two parallel wires connected to the same side of the transformer, and at a constant spacing s of 120 cm. from the conductors of the opposite line; 180,000 volts is impressed between lines. Both front and edge view is shown. (1) shows the two wires of same potential 2.54 cm. apart. (2) shows the wires 1.27 cm. apart and much less corona than on (1). (3) shows the wires very close together, and that the corona has increased again. The critical voltage is maximum, therefore, for spacing somewhere between (2) and (3). Note that the coronas are repelled out and the space between the two wires is dark. A somewhat similar thing takes place on a stranded cable where the critical voltage is much higher than the critical voltage of a single strand, but somewhat lower than a solid conductor of the same outside diameter.

Fig. 43 means that when conductors of a given polarity are placed near other conductors of the same polarity the critical voltage is increased, also that there is a certain best arrangement of conductors for maximum e_v.

XII. GENERAL REMARKS

While the experiments and deductions included in the present paper throw a great deal of additional light on the mechanism of corona formation and loss there is still considerable work to do, both from an experimental and theoretical standpoint. It was thought best, however, in order to make the results most useful, to put them in the hands of other investigators as soon as obtained, and in their present form.

Extensive experimental investigations are still being planned and carried on. These have a bearing on theoretical work done, but not included here. Of special interest will be the effect of frequency on power loss and visual corona, over a very wide range, corona at continuous impressed volts, etc.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

THE ELECTRIC STRENGTH OF AIR—III

BY J. B. WHITEHEAD

The two earlier papers of this series discussed more particularly the conditions governing the start of the high-voltage corona. This line of investigation is continued to some extent in the present paper. In addition some interesting observations of the properties of the full-formed corona itself are recorded.

The work described in these papers has as its principal object a further knowledge of the physical laws underlying the widely diverse manifestations of the breakdown of the air under electric stress. Several results described in the earlier papers, *e.g.*, the influence of moisture, of atmospheric pressure, and of stranding the conductor, have had a direct practical bearing. For the most part, however, the results are of only indirect value to engineers, since they are concerned rather with the ultimate nature of the corona. For this reason, and also because in Institute discussions of corona phenomena some indifference has been expressed to the introduction of the language of present accepted theories of gaseous conduction, the results of the present paper are offered to the Institute with some diffidence. The writer is encouraged, however, by a conviction that the electrical engineer can no longer afford to rest content with observed facts and laws, or as one has expressed it, to be "satisfied with the volt-ampere characteristic," leaving investigation and explanation to the physicist. However true this may be for other branches of engineering, the position is not tenable for us. For in every direction we are face to face with unexplained facts and unexplored fields of investigation. And we have at our disposal apparatus and a range of variation of the quantities involved which are usually denied the physicist by his lack of engineering training. We can perform lasting service by extending the limits within which existing theories have been tested and by exploring phenomena which seem to fall under no theory. Thus the investigations described in these papers have been undertaken partly under the attraction inherent in journeys into new country, but also in the certainty that the laws of corona formation can be obtained only by controlling all the attendant conditions. A more intimate study is necessary than is possible on transmission lines in the open, or in other instances where the range of observation is restricted to one set of conditions containing many elements.

The present experiments may be divided into three classes. The first is a study of the nature of the conductivity or ionization of the air in the neighborhood of the corona. The second, the determination of the diameter of the corona for several particular cases. The third, an investigation of the influence of the subdivision of a conductor on the corona-forming voltage.

THE IONIZATION DUE TO THE CORONA

In the experiments with cylinder and central wire described in the earlier papers it will be recalled that the conductivity imparted by the corona to the air, in discharging an electroscope, afforded an accurate means of observing the initial breakdown of the air. It was noticed that the electroscope acted equally well as an indicator of the first presence of corona whether charged positively or negatively. With increasing alternating voltage and corona volume there was some indication that the discharge was more rapid when the electroscope was charged negatively. The time of complete discharge is so short, however, when the voltage is pushed even slightly above the critical value, that the electroscope becomes unsuitable for studying this peculiarity. A less sensitive instrument is necessary. In the arrangement of apparatus shown in Fig. 1 the wire *A*, on which the corona forms, lies along the axis of a woven wire cylinder *B*, 17.13 cm. in diameter and 120 cm. long. The wire of the cylinder was No. 19 B.&.S. gage and the square mesh opening 0.8 cm. on a side. No appreciable alteration of the symmetrical field inside the cylinder is caused by the openings. Corona voltages measured with this cylinder agree with those taken with the same wires in solid wall cylinders. An outer sheet metal cylinder *C*, 17.8 cm. in diameter and 50 cm. long, was placed outside the wire mesh cylinder *B*, and suspended from two sulphur insulators, *D*. This cylinder therefore formed a large insulated electrode for collecting the charge which, originating as ions in the corona,escapes under the velocity of the electric field through the openings in the wire cylinder. Screens *S S* restrict the charge collected to that originating from a constant length of wire. The wire cylinder was connected to ground throughout the experiments. The outer cylinder was connected through a D'Arsonval galvanometer giving a deflection of one mm. at 2×10^{-7} amperes, to either the positive or negative terminal of a variable source of continuous potential, the other terminal being connected to ground. When no field is applied between *B* and *C* any charge that reaches *C* is due to the velocity acquired by the ions or charged particles of air while inside the cylinder *B* and so under the influence of the electric field between *A* and *B*. When a continuous potential difference is applied between *B* and *C*, and when a corona exists on the wire *A*, the resulting charge which flows away from *C* is of sufficient magnitude to give large deflections in galvanometers of moderate sensibility. Evidences of ionization or conductivity may be detected by the electroscope at distances of 30 cm. or more when the cylinder *C* is removed, but in order to bring the current corresponding to the continuous rate at which the charge reaches *C*, within range of ordinary galvanometers, the separation between *C* and *B* should be small. Obviously when *C* is charged positively it will collect negative ions, and vice versa, and the greater the potential to which *C* is raised, positive or negative, the greater will be the proportion of ions which, escaping through *B*, will reach *C*.

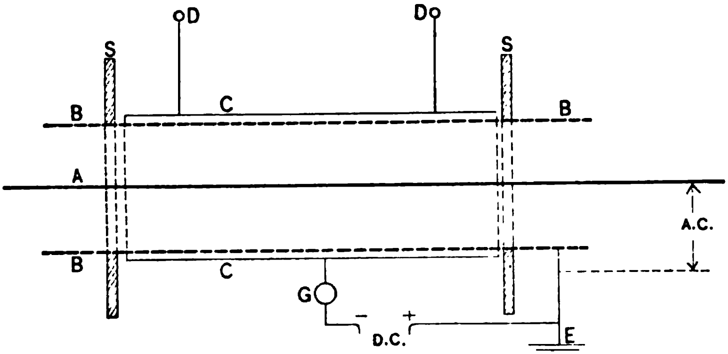


FIG. 1—POSITIVE AND NEGATIVE IONIZATION OF THE CORONA.

The first experiments were made with a 0.152-cm. polished copper wire. The corona started on this wire at about 63 volts on the primary of the step-up transformer of ratio 1 : 250. Voltage control was obtained with an induction regulator. The wave shape was closely sinusoidal. As the study is purely qualitative the observations are omitted and the results are plotted in curves with the quantities as read on the several instruments as coordinates. Fig. 2 shows three curves plotted between galvanometer deflection and values of continuous negative potential up to 120 volts applied to the outer cylinder *C*. The three curves were taken with 80, 100 and 120 volts, respectively, on the transformer primary. The curves show by their intersection with the axis of zero continuous potential the interesting fact that at low alternating voltages, that is, in the neighborhood of the start of corona, an excess of positive ions reaches the opposite conductor, whereas with increasing alterna-

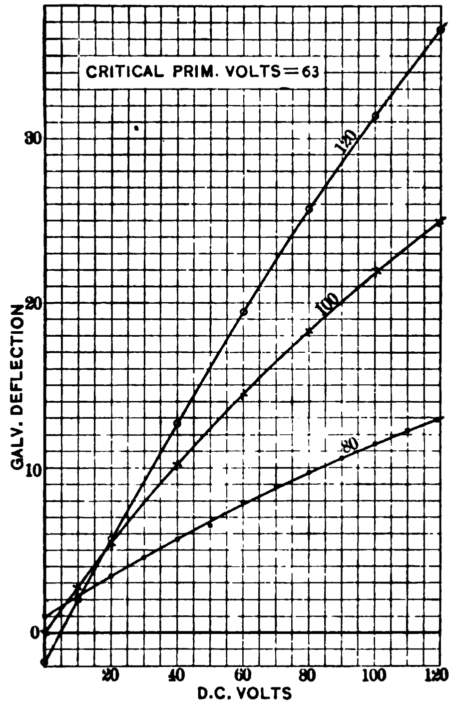


Fig. 2—Positive Ionization from Corona.

ting voltage the sign of this excess changes to negative. Thus with no voltage between the outer cylinder and ground and with alternating voltage only slightly above that at which corona starts, there is a small but definite positive charge collected on *C*; with increasing alternating voltage the sign of this charge changes to negative. The values of these charges are small, as a low value of continuous negative potential between *B* and *C* masks the difference except in so far as indicated by the intersections of the curves. The curves also show that at 120 volts between *B* and *C* the galvanometer deflections are still increasing rapidly with the voltage, indicating that only a fraction of the total conductivity or ionization generated by the corona is collected by *C*.

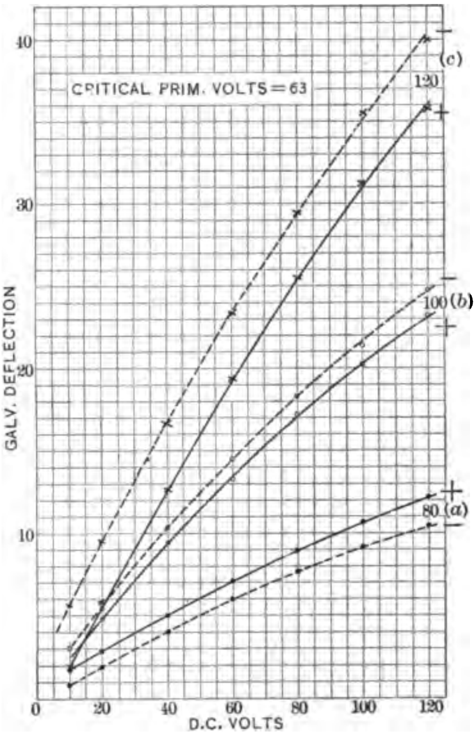


FIG 3—POSITIVE AND NEGATIVE IONIZATION FROM CORONA.

The curves of Fig. 3 show for the same alternating voltages the results with *C* at different values of positive and negative potential with reference to *B*. The solid lines indicate positive charge, the dashed lines the negative charge collected on *C*. The curves *a* for 80 volts (primary) show that the excess of positive charge at low alternating voltage, shown in Fig. 2, is independent of the potential of *C*. The curves *b* and *c* show that there is a reversal of sign of the excess charge reaching *C* between 80 and 100 alternating primary volts, and that the excess of negative charge increases with further increasing alternating voltage.

A further series of observations was taken for the values of alternating voltage between 63, the primary voltage at which corona begins, and 120, with *C* at various positive and negative potentials. The curves are similar to those of Fig. 3 and are omitted from that figure in order to avoid confusion. They also show, in agreement with the observations described in the first paper of this series, that there is no ionization before corona starts. They show further that at 97 volts the curves for positive and negative potentials of *C* coincide, *i.e.*, that the excess of ionization changes sign at this voltage.

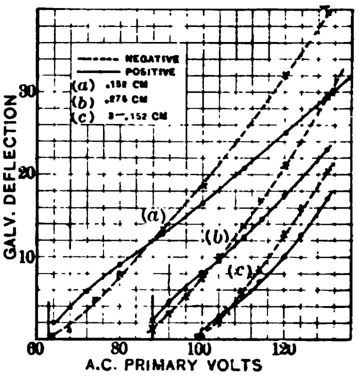


FIG. 4—IONIZATION FROM CORONA.

The curves of Fig. 4 show, for 0.152-cm. and 0.276-cm. wires, the variation between current received at the electrode *C* and alternating primary voltage up to 130, with *C* maintained at 100 volts continuous potential; solid lines *C* negative, dash lines *C* positive. They show that when corona starts a small though appreciable stream of positive ions immediately reaches the opposite conductor; beginning with this value the intensity of the positive stream increases at first sharply, but with decreasing rapidity, then approximately linearly, with the elevation of alternating voltage. The negative stream appears to begin with zero value at the start of corona but to increase more rapidly than the alternating voltage and therefore crosses the line showing the behavior of the positive stream. The third pair of curves in Fig. 4 is plotted from a series of observations with a central conductor consisting of three 0.152-cm. wires arranged in form of an equilateral triangle 0.62 cm. to a side. These curves will be commented on later in this paper. At present it need only be noted that they have the same characteristics as those for the single wires.

The charge received on *C* and read as current on the galvanometer is an indeterminate portion of the total which would reach the cylinder *B* if there were no openings in it. Consequently the actual current values read on the galvanometer can have no direct bearing on the current passing between *A* and *B*. However, if the potential of *C* is maintained at the same value throughout a number of tests on different conductors, the curves between galvanometer current and alternating voltage may be used as an approximate method of comparing the relation between voltage and conduction current and therefore power loss for the several conductors. Thus from Fig. 4 it is not unreasonable to conclude that the power loss increases with the voltage in approximately the same relation for each of the three conductors there indicated, since the galvanometer current represents approximately the same proportion of total loss current in each case.

The amount of free ionization in the air has often been suggested as having an influence on the corona-forming voltage. The author has already shown several reasons why this cannot be so, among them being the cessation of corona with the decreasing voltage of each half wave, the cessation of corona at the same voltage at which it starts, and the independence of the corona voltage of the ionization about the wire, set up by Rōntgen rays. A simple experiment bearing further on this question was performed as follows:

A clean copper wire 0.157 cm. in diameter centered in a 15.2-cm. tube started corona at 58.5 primary volts. This wire was then enclosed successively in thin paper tubes of 2.54-cm., 1.27-cm., and 0.95-cm. diameter. These tubes were slightly longer than the outer cylinder and were insulated and held accurately concentric by means of three silk threads at each end. The tubes were made of tracing paper cut in long strips and spiralled so that when suspended horizontally from the ends there was no observable sag at the middle point. Ions in the region outside these tubes would therefore be prevented from reaching the wire, and if these ions have any influence on the corona voltage we should expect an elevation of this voltage when the wire is screened as above. No change in the corona voltage was observed when the largest tube was in place. In the case of the smaller tubes the corona voltage was lower by 1.5 to 2 volts than when the tubes were not inserted. In this experiment the number of ions in the neighborhood of the wire is lower when the paper tube is in place, since the tube prevents the ions moving under the influence of the electric field, from reaching the central wire. Consequently we should expect an elevation instead of a lowering of voltage, if the presence of ionization facilitates the formation of corona. The lowering actually observed is probably accounted for by the increased gradient near the wire due to the presence of the thin layer of paper of higher specific inductive capacity than the air. It may be concluded from the experiment that the ionization in the air at a distance from the wire has no influence on the corona-forming voltage.

The properties of the ionization emanating from the central wire were also investigated further by a return to the apparatus with solid outer cylinder 18.6 cm. in diameter. A small slit cut in this cylinder was placed opposite a like opening in a large closed box as shown in Fig. 5. An insulated electrode connected with the electroscope could be shifted to various positions in the box. It was found that the electroscope was discharged slowly when the electrode was placed anywhere in the box but far more rapidly when the electrode was located on thel ine passing through the corona and the opening in the box. The rate of discharge falls off as the electrode is moved away from the opening but may readily be detected at 30 cm. or more.

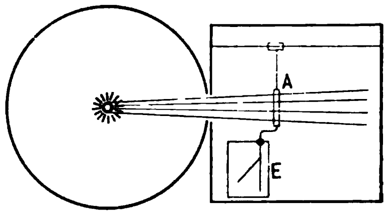


Fig. 5—Nature of the Ionization of the Corona.

Glass or the thinnest tissue paper placed over the opening completely screens the electroscope from any influence of the ionization. Further, if a screen of paper is suspended by threads in front of the opening it is blown away with increasing force as the voltage is raised above that at which corona starts. Below this voltage there is no effect on this paper screen.

The above results show that there is a distinct motion of air away from the corona. That this air carries both positive and negative charges. That it tends to move in straight lines, but that it diffuses or scatters in all directions away from the central beam. Any material obstacle will completely stop this motion. These facts are in accord with the ionization theory and the phenomena may be identified in all respects with the well-known properties of gaseous conduction. Some further discussion of the results will be given at the end of the paper.

DIAMETER OF THE CORONA

Visual Method. When formed on a perfectly smooth clean wire, the corona presents a uniform appearance. While the boundary is not sharply marked, from a short distance there is quite a suggestion of a uniform diameter. The slightest surface imperfections, however, are indicated by variations in color and diameter of the corona. On small wires the core of the corona has the pink tinge characteristic of other forms of electric discharge in air, shading off to violet of lessening intensity towards the boundary. On larger wires the region at the surface of the wire does not appear so bright or dense, but there is a constant play of intermittent thread-like sparks from the wire toward the boundary. There is quite a suggestion of transparency. Notwithstanding the gradual shading off in intensity toward the outer regions, the uniform corona gives a distinct impression of a definite diameter. It may be conveniently studied by the central wire and cylinder method, by cutting small slots in the cylinder, or by making the cylinder of wire mesh. With the cylinder connected to earth close inspection is possible.

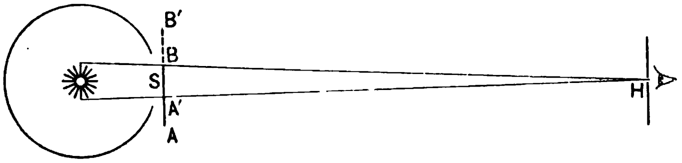


FIG. 6—METHOD OF MEASURING THE DIAMETER OF THE VISIBLE CORONA.

A number of measurements of the diameter of the visible corona were made following the direct optical method described in the first paper. The method is indicated in Fig. 6. A vertical slit S, 2 cm. wide, was cut in the horizontal outer cylinder of 18.6 cm. diameter. A screen wide enough (1.9 cm.) to obscure the corona was attached to a cathetometer permitting its motion up or down in a plane close to the slit. With the eye at a pinhole H, the screen was gradually moved upward from below until the top edge of the corona disappeared, as in the position *AB*, then the screen was moved downward from above to the position *A'B'*, in which the lower edge was completely obscured. The width of the screen was 1.9 cm., the distance from the wire to the screen 9.8 cm. and from screen to eye 785 cm. These data permit ready calculation of the apparent diameter of the corona. The experiments were made with a 0.233-cm. diameter wire centered in an 18.6-cm. cylinder and the corona started at 23,250 effective volts. A number of determinations of diameter were made at several voltages. Only those at 32,500 volts will be given, as read on different days.

TABLE I. VISIBLE DIAMETER OF CORONA. 0.233-CM. WIRE IN 18.6-CM. CYLINDER.

Top	Bottom	Top	Bottom	Top	Bottom
70.85	72.16	70.88	72.27	70.94	72 2
70.88	72.18	70.88	72.22	70.94	72.22
70.85	72.18			70.95	72.16
70.86	72 18			70.92	72.18

Successive settings on any one occasion show a very satisfying constancy, but the results on different days vary somewhat. Thus the mean differences of the above sets are 1.32, 1.38 and 1.25; these give a mean value of 1.31 with a maximum variation of 5 per cent. The corresponding diameter of the corona is about 6.7 mm. From the rough experiment described in the first paper it appeared that the diameter of the corona was very nearly that of the solid conductor which would just begin to form corona at the voltage giving the corona whose diameter was measured. The present experiments, which were more numerous and made with greater care, indicate that this approximation is not so close as suggested by the earlier result. The critical voltage of a conductor 0.67 cm. in diameter placed in an 18.6-cm. cylinder is about 37,000, whereas the voltage of the corona 0.67 cm. in diameter (on a 0.233-cm. wire) was, as stated above, 32,500. From this it appears that while the conductivity of the corona is high, there is nevertheless an appreciable loss in it. The experiments on the visual measurement of the diameter were not carried further. With practise and care quite consistent results may be obtained, but the following photographic results indicate that the visible corona probably does not mark the boundary of the region in which the air is breaking down.

Photographic Method. No extensive attempt to measure the diameter of the corona by photographic methods appears to have been made. Jona mentions the failure of his attempts in his paper before the St. Louis International Electric Congress in 1904. Such methods have properly been regarded with suspicion owing to the want in definiteness of outline, the importance of the time element in the exposures, the ultra-violet content of the corona, etc. The best possibilities of the method do not, however, appear to have been developed. In the present experiments careful cleaning of the wire has resulted in very uniform photographs, which while lacking definite lines of corona boundary nevertheless give the impression that this boundary lies within comparatively narrow limits. They are quite suitable for comparing the diameters corresponding to various voltages.

Two types of lens were used. The first was a fine portrait Steinheil of 13 cm. aperture and 30 cm. focus, which gives excellent definition, but which naturally does not transmit the ultra-violet end of the spectrum. The second lens was a Zeiss achromatic of quartz and fluorite, aperture 3 cm., focus 40 cm., and which transmits all wave-lengths down to 0.00018 mm. The corona was exposed through an opening 8 cm. long and 2 cm. wide in the 18.6-cm. cylinder, whose interior was coated with lamp black to prevent reflection. Some of the results are shown in Figs. 7 to 12. Fig. 7 shows the influence of time of exposure; *a*, *b*, and *c* are exposures of one, two and three minutes respectively with the glass lens, of the corona formed at 32,500 volts on the 0.233-cm. wire; the critical voltage for the wire is 20,750. The exposures were made in quick succession on the same plate, and all were developed and fixed together. This method was followed with all the exposures which are compared with each other. The exposure *c* has apparently the greatest diameter. On inspection under a glass, however, the plate shows that the limits of *b* and *c* are about the same, although *c* is naturally the denser. For comparative purposes, therefore, two-minute exposures were used. Fig. 8 shows the coronas on the same wire at 22,500, 27,500 and 32,500 volts respectively with one-minute exposures, and Fig. 9 the same with two-minute exposures. Corrected to actual size the diameters of the coronas at the three voltages as taken from the two-minute exposures are 5.5 mm., 9.3 mm. and 11.1 mm. respectively. These diameters mark the limit to which the emulsion of the plate is affected, as observed under a strong reading glass. Obviously the values are therefore only approximate. However, four independent observations of exposure *c* resulted as follows: 10.9, 11.1, 11.2, 11.2, giving the mean 11.1 mm., and indicating an inaccuracy of only 2 or 3 per cent. By the direct visual method the diameter of the visible corona under the same conditions was 6.7 mm.

A number of exposures were then made with the quartz-fluorite lens. Owing to the smaller aperture the exposures were much longer, from 20 to 40 minutes. In order to secure a direct comparison between exposures with and without the ultra-violet content, one half of the plate was screened with a thin piece of clear glass which does not transmit the ultra-violet. Some of the results are shown in Fig. 10, in which the exposures were 20 minutes long; the exposures *a*, *b* and *c* were taken with 32,500 volts on wires of diameters 0.232, 0.316 and 0.399 cm. respectively. The transverse bands of lesser intensity are due to two strips across the opening in the wall of the outer cylinder, to prevent possible distortion of the uniform electric field. The broader portions to the left on each exposure give the effect of the entire visible spectrum with ultra-violet added; the narrower right-hand portions show the effect of cutting out the ultra-violet with a piece of ordinary plate glass. The diameters, as measured from the plates with the aid of a glass in the manner described above, are given in Table II.

TABLE II

DIAMETERS OF CORONA, WITH AND WITHOUT ULTRA-VIOLET CONTENT.

0.232-cm. wire		0.316-cm. wire		0.399 cm. wire	
Quartz and glass	Quartz alone	Quartz and glass	Quartz alone	Quartz and glass	Quartz alone
12	12.4	12.5	13.3	11.4	13
11.5	12.6	13	14	11.6	13
11.5	12.6	13	14	12	12.8
11.4	13	12.8	14	12	12.8
11.6	12.6	12.8	13.8	11.7	12.9

As stated above, all the observations in Table II were taken at 32,500 volts, which is well above the critical voltage for the largest wire. It is interesting to note that within the limits of accuracy (about 5 per cent) of the method of measuring the diameters, the coronas on the above three wires at the same voltage have approximately the same diameter both in the visible

PLATE LXIV
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FIG. 7

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FIG. 8

[WHITEHEAD]

FIG. 9

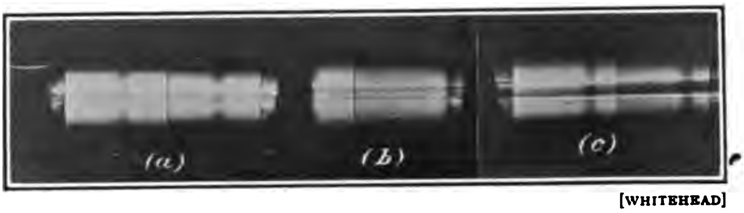

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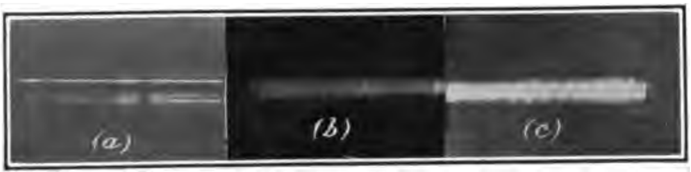
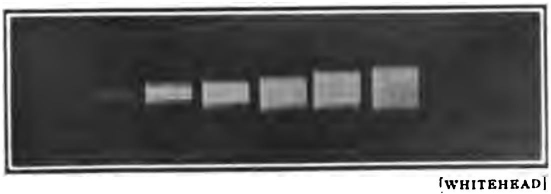
FIG. 10



[WHITEHEAD]

FIG. 11



[WHITEHEAD]

FIG 12

and ultra-violet. This fact has also been noted by Jona, who estimated from the appearance at a distance that several wires of different diameters subjected to the same voltage formed coronas of equal diameter. The diameter for the 0.232-cm. wire taken over 20 minutes is seen to be in fair agreement with that taken over three minutes with the glass lens. It is not probable that there are present any shorter wave lengths than those transmitted by the Zeiss lens. The presence of Röntgen rays has been suggested. To test this question a very sensitive plate was wrapped in one thickness of black paper, and placed directly against the opening in the outer cylinder. After 20 minutes' exposure the plate was found to be entirely unaffected, showing that Röntgen rays if present must be in very small amount and degree of penetrating power.

Fig. 11 shows two observations of interest. The first, *a*, is the corona on the 0.399-cm. wire at a voltage very slightly above the critical or corona-starting value. As transmitted through glass the corona shows little more than the outline of the wire. Through the quartz lens, however, without the interposition of glass, the corona is seen to have a diameter over twice that of the wire. This is in accord with common observation that the visible corona starts suddenly, and from the beginning appears to have an appreciable thickness. The reproduction of the print from this negative is not very satisfactory, but the plate itself reveals the above fact. The other exposures, *b* and *c*, of Fig. 11 show a curious result for which no explanation has been found. The spiral form of the corona shown was observed and photographed several times with this particular wire. Between observations the wire (a 0.233-cm. steel rod) was removed, carefully polished, and examined for surface peculiarities. Nothing was observable under the microscope, but by reflected light the surface gave evidence of slight circumferential corrugations. Since these corrugations had no spiral they do not appear to be a complete explanation of the several photographs. The depth of the spiral and sharply marked threads is especially interesting in view of the extremely minute variation in the apparently smooth and uniform surface of the wire.

Considering, then, these several methods of estimating the diameter of the corona we find that the visual method gives the smallest value. A photographic determination with the usual type of glass lens gives a diameter larger in the approximate ratio 1 : 1.6. With the ultra-violet down to 0.00018-mm. wave length included, the photographic method gives a further increase over the visible diameter in the ratio 1 : 1.9. The absence of Röntgen radiation suggests that there is little other radiation shorter than that transmitted by the Zeiss lens and therefore that the ultra-violet corona marks the limit of the region in which ionization is taking place.

Fig. 12 shows a series of two-minute exposures with the glass lens of the corona on the 0.233-cm. wire in the 18.6-cm. cylinder at primary voltages 90, 100, 110, 120, 130 and 140 volts (ratio of transformation 1 : 250). The critical primary voltage was 86. The diameters were measured from the plate under a glass as described above. Corrected so as to include the ultra-violet by the factor 1.18 the diameters are plotted in relation to the primary volts in Fig. 13. Apparently the diameter increases sharply at the critical voltage, then more slowly, and finally in a linear relation with the voltage.

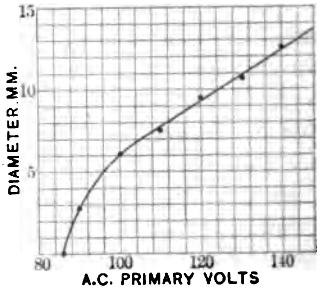


FIG. 13—DIAMETER OF CORONA.
0.233-cm. wire in 18.6-cm. tube.

THE CORONA VOLTAGE OF SUBDIVIDED CONDUCTORS

One of the most interesting questions in connection with the formation of corona is the explanation of the simple law given in the second paper of this series, connecting the critical surface potential gradient and the diameter of the conductor. The ionization theory of gaseous conduction and discharge accounts for so many of the observed phenomena that it is practically universally accepted. So far, however, the theory has not been brought into accord with all the phenomena of corona formation, and indeed some of the observed facts are in direct opposition to the tenets of this theory. As regards the influence of temperature and pressure observation and theory appear to be in accord. But the influence of the curvature of the conductor, and the apparent absence in corona formation of an influence of the amount of free ionization, remain to be explained. As regards the former various suggestions have been made, as for example, a condensed layer of air near the conductor, the concentration of ions under the strong electric field at the surface, etc., as suggested by the author. As between these two suggestions it should be possible to draw a conclusion from the combination of a circular conductor and a field which is not symmetrical about it, provided the surface potential gradient corresponding to a given voltage can be calculated. For if a condensation layer is involved the critical intensity should be the same in the symmetrical and unsymmetrical fields, while if the density or motion of existing ionization is involved a difference in the critical intensities in the symmetrical and unsymmetrical cases would be probable.

The following experiments were undertaken partly with the aim to distinguish between the two ideas above noted. They consisted in observations of the corona voltage of three or more wires in parallel arranged at the corners of equilateral figures, and symmetrically placed on the axis of the surrounding cylinder. It was also realized that in this arrangement the equipotential surfaces, proceeding outward from the central wires, would tend to approach the circular form; or in other words that the potential gradient near the surface of one of the component wires corresponding to a given voltage, would be less with the multiple wire arrangement than with a single wire, owing to the influence of the other wires. Consequently several wires in parallel might require a higher voltage for breakdown than a single wire of section equal to that of all the others. The results of the experiments do not shed much light on the cause of higher critical intensities of small wires, owing to the difficulty of calculating the intensity corresponding to the various voltages observed. They indicate, however, that the air near a wire of circular section may require different values of electric intensity for breakdown. They also show an interesting relation between the critical voltage of a single conductor and that of three and four wires of equal aggregate cross-section, arranged in a symmetrical figure and connected in multiple.

The first experiments were made with three 0.152-cm. wires in the 17.2-cm. diameter wire mesh cylinder already mentioned. The wires were arranged at the corners of equilateral triangles with circumscribing circles of radii between 0.47 and 1.58 cm. The galvanometer was used as detecting instrument, the connections being shown in Fig. 1. The maximum primary voltage at which corona started was 105.6 for the triangle of radius 0.7-cm. The corona voltage of a single 0.274-cm. wire which is approximately equal in section to the three wires used was 91.6 volts. Thus the corona voltage for the three wires was 15.3

per cent higher than that of the single wire of equal cross-section. The ionization experiments in the first section of the paper and the curves of Fig. 4 show that the leakage loss due to the ionization resulting from the corona varies in the same way with increasing voltage for three wires as with one wire.

Considerable difficulty was found in the foregoing experiments in maintaining uniform spacing and tension of the three wires. Further experiments were therefore arranged, using three 0.238-cm. steel rods hung vertically and each provided with individual screw thread adjustment of tension. They were placed in a 29.2-cm. cylinder in triangles of radii from 0.3 to 2.54 cm. In these experiments the visible corona was used as detector of the critical voltage. The voltage was obtained from a 100,000-volt 10-kw. transformer fed from a generator excited from a storage battery and driven by a direct-connected motor. The voltage was read at the terminals of a low-tension secondary coil. The ratio of transformation was 1 to 833.36. The method of observation, carried out in a completely darkened room, was to increase the current in the generator field gradually until corona appeared as viewed through a small opening in the wall of the outer cylinder. The voltage was read simultaneously by a separate observer. The observations are given as taken, in Table III. In the fourth column the mean value is corrected to 21 deg. cent. and 760 mm. pressure. The table also includes the results of contemporaneous observations on single wires of 0.238, 0.397, and 0.476 cm. diameter. The nearest of these to a cross-section equivalent to that of three 0.238-cm. wires is

TABLE III

CORONA VOLTAGES OF THREE 0.238-CM. WIRES IN PARALLEL, PLACED AT APEXES OF EQUILATERAL TRIANGLES.

Conductor	Radius of triangle cm.	Volts			Factor	Max. sec'y intensity
		Observed	Corrected	Max. sec'y.		
0.238 cm.	——	26.7	25.8	33,300	—	59,800
0.397 "	——	36.1	35.1	45,300	—	53,270
0.412 "	——	(Calculated)	35.7	46,200	—	52,860
0.476 "	——	40.7	39.6	51,100	—	51,400
3-0.238	0.317	41.1, 40.6, 41.1	39.6	51,200	1.38	70,700
"	0.634	42.7, 42.7, 42.6	41.5	53,700	1.21	65,500
"	0.952	42.1, 42.2, 41.6	40.7	52,600	1.17	61,500
"	1.27	41.7, 41.7, 41.4	40.5	52,500	1.11	58,300
"	1.58	40.9, 41 , 40.5	39.5	51,100	1.16	59,400
"	1.90	39 , 39.7, 38.9	38.2	49,400	1.22	60,600
"	2.54	38 , 38 , 37.5	37	47,850	1.3	62,500

0.397; correcting the observation for the 0.397-cm. wire to the true cross-section indicates a value of critical volts 46,250. The observed critical voltage for the three 0.238-cm. wires has a maximum value for the triangle 0.63 cm. in radius. This value was 53,700, that is, an increase of 16.3 per cent over that of the single wire of equal aggregate cross-section.

The observations of Table III, together with those of another series taken with the same wires, are plotted in Fig. 14 between test coil volts and radius of triangle. While the observations for any one arrangement were found to be very uniform, it will be noticed that the points do not fall at all regularly on a continuous curve. A large number of repetitions for different sizes of triangles failed to eliminate this trouble. The explanation was found in the impossibility of adjusting the wires to uniform tension throughout the different sizes of triangle. It was found that the electrostatic repulsion between the wires caused them to spread apart in varying degrees. A number of light brass separators of triangular shape were used but they only lessened the trouble slightly. Each series of observations, however, resulted in showing that the critical voltage for three wires was invariably in the neighborhood of 16 per cent higher than that for the single wire of equal aggregate section and this maximum elevation occurred when the wires were at the corners of a triangle lying within a circle of 0.63 cm. radius as measured at the ends. This means that the wires were separated by approximately five diameters. The electrostatic spreading could not be determined but the actual separation was somewhat greater than stated.

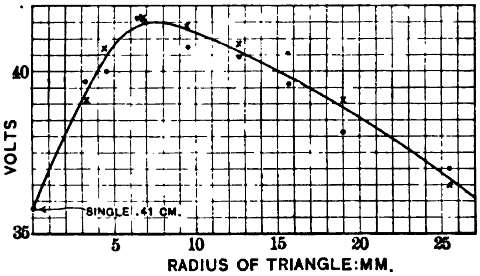


FIG. 14—CORONA VOLTAGE.
Three 0.238-cm. diameter wires in parallel.

A series of experiments was also conducted on four 0.238-cm.

rods arranged in the figure of a square, the sizes of these squares being such as just to lie within circles of 0.635 cm. to 10.6 cm. radius, otherwise the apparatus, method of operation, etc., was the same as that described for the three wires. Separators were also used to reduce the electrostatic spreading. The observations are given in Table IV, showing the variation of critical test coil volts with the diameter of a circle passing through the centers of the four wires. The critical voltage for a single 0.467-cm. wire which is equal to four 0.238 cm. wires is also given. These results indicate that the maximum corona voltage for the four wires occurs when they are arranged on a 3.3-cm. circle and that the approximate elevation of voltage for four wires above that of a single wire of equal section is 20 per cent. It will be noticed that the diameter of the circle giving maximum voltage is much greater for four wires than for three.

The last three columns of Table III give, first, the secondary voltage, maximum value corrected for wave form; second, the factors which multiply the maximum secondary voltage in order to give the maximum surface intensity on each wire, and in the last column, the values of this maximum surface intensity. The correction for wave form was made by referring the observations on three sizes of single wire to formula (1) of the second paper of this series, connecting maximum critical surface intensity with the diameter of the wire. The method of calculating the factor given in the next to the last column will be described later in the paper. It will be noted that the last column indicates that the maximum intensity occurring on the surface of the wires decreases from 70,700 to a minimum in the neighborhood of 59,000 and then apparently begins to increase again. The critical surface intensity for a single wire of the same size as the three used is 59,500. It is apparent, therefore, from these results that the critical surface intensity is not necessarily a constant for a given size wire but depends in large measure on the configuration of the field, due to neighboring conductors.

TABLE IV
CORONA VOLTAGES OF FOUR 0.238-CM. WIRES IN PARALLEL AND PLACED ON CORNERS OF SQUARES.

Radius of circle, cm.	0.63	1.27	1.90	2.54	3.17	3.81	5.08
Volts	85.2	94.1	94.9	94.6	95	92	90.5
Critical volts for single 0.476-cm. wires = 78.8							

It is further evident that by subdividing the total cross-section of a given conductor into a number of smaller conductors and arranging them suitably, the critical voltage may be raised in considerable amount. The simplest arrangement, that of three wires, results in an elevation of 16 per cent. It is open to some question whether it would be possible to take advantage of these facts in actual transmission lines. It is quite probable, however, that the principle would be available in the case of solid and liquid dielectrics. It is also worth noting that a similar subdivision of the total cross-section of a transmission conductor has been suggested for the purpose of adjusting to best advantage the ratio of inductance and capacity of transmission lines.[1]

DISCUSSION

It is of interest to speculate upon the explanation of the excess positive charge due to corona near its start, and the change of this excess to the negative sign with higher values of alternating voltage. It has been noted that there is a difference in the corona for positive and negative continuous voltages and it is therefore not impossible that the corona may start at a somewhat different voltage on each half of the alternating wave. If we assume, as is practically certain, that the initial ionization is due to the collision between a molecule and a negative electron, we have a very probable explanation of the observed results. The electron must attain its critical velocity when moving inward toward the wire, since the intensity of the field increases in that direction. This being so the corona would start when the wire is positive; therefore the positive ions would be repelled. It is only necessary to assume a slight difference in the critical voltage for the two halves of the wave to explain the first appearance of the positive ion. Indeed, the fact that the negative electron is invariably the first ionizing agent and the additional fact that field increases towards the wire makes it certain that the first corona appears when the wire is positive.

For increasing value of voltage, the corona forms on both half-waves and the charge reaching the outer cylinder is the resultant due to both half-waves. Negative ions move faster than positive, hence, when both half-waves are active, there will be an increasing excess of negative charge appearing. The relative behavior of the positive and negative excess may be seen from the curves of Fig. 4.

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[1] P. H. Thomas, TRANSACTIONS A.I.E.E., 1909, Vol. XXVIII, I, p. 641.

Referring to the experiments with small paper tubes surrounding the wires, the failure of these tubes to cause an elevation of the critical voltage apparently indicates that this voltage is to a large extent independent of the number of free ions in the atmosphere. It also shows that the suggestion that ions may bank up in the neighborhood of the wire, thus lowering the surface intensity, is hardly tenable as an explanation of the law expressed by formula (**1**) of the second paper, connecting critical surface intensity with diameter of the wire. In order to test this suggestion further, a calculation has been made of the lowering of the surface intensity corresponding to a given voltage, caused by the attraction to the surface of all of the ions which commonly exist in the atmosphere.

The greatest distance from which an ion will reach one wire subjected to alternating voltage may be conveniently investigated for the case of two parallel wires of radius r and distance D apart. If V is the instantaneous voltage and v is the specific velocity of an ion, that is, its velocity in cm. per sec. per volt per cm., we have:

$$\text{Gradient at distance } r = \frac{V}{2\,r \log \frac{d}{a}}$$

$$\text{velocity, } v, \text{ at } r \text{ at any instant } t = \frac{v\;V_0 \cos n\,t}{2\,r \log \frac{d}{a}}$$

$$\text{In time } dt, \text{ distance traversed, } dr = \frac{v\;V_0 \cos nt\,dt}{2r \log \frac{d}{a}}$$

$$\therefore\; 2\,r\,dr = A \cos nt\,dt;\ \text{where } A = \frac{v\;V_0}{\log \frac{d}{a}}$$

$$\therefore\; r^2 = \frac{A}{n} \sin nt + C$$

$$\text{Now } v = o \text{ when } V = O, \text{ and } nt = -\frac{\pi}{2}$$

$$\therefore\; c = \frac{v\;V_0}{n \log \frac{d}{a}} + a^2$$

$$\therefore\; r^2 = \frac{v\;V_0 \sin nt}{n \log \frac{d}{a}} + \frac{v\;V_0}{n \log \frac{d}{a}} + a^2$$

Thus r has its greatest value when $nt = \frac{\pi}{2}$

and is given by $r^2 = \dfrac{2v\,V_0}{n \log \dfrac{d}{a}} + a^2$

From a set of experiments by Peek and Steinmetz in which a was 0.538 cm. and d was 304.8 cm., the visible corona voltage was found to be 157 kilovolts at a frequency of 60 cycles per sec. Taking the value of v, the velocity of the ions, at 1.5 cm. per sec. per volt per cm., the value of r^2 is found to be 276. This means that, under the conditions of the observation, at the time the corona started every ion within a distance of 16 cm. from the wire would be drawn to the surface of the wire between the zero and maximum values of any half-wave. Under normal conditions there are about 1000 ions to every cubic cm. of air, the range of variation being to about four times this number. The charge on each of these ions is 4.6×10^{-10}. With these figures in mind the charge per unit of surface resulting from the attraction of these ions to the surface may be calculated and the value of this charge is found to be 4×10^{-4} c.g.s. electrostatic units per unit of length. From this the value of the surface electric intensity due to this accumulated charge is found to be only from 0.5 to 2 volts per cm. or entirely negligible as compared with critical corona-forming intensity. We may conclude therefore that the attraction of the ions ordinarily existing in the atmosphere to the surface of the wire is not the explanation of the elevation of the critical intensity observed with smaller wires.

Referring again to Table III it has been already stated that the last column gives the values of the maximum critical surface intensity occurring on each of the three wires for different sizes of triangular figure. These values have been obtained by multiplying the maximum value of the critical voltage by the factors given in the next to the last column, and these factors have been deduced for an exact case to which the arrangement of three circular wires only approximates. The fact that the results show that the air breaks down at different values of electric intensity for a single size of wire is important in the indication it carries of the nature of the factors governing the breakdown. It is therefore necessary to examine the process by which the multiplying factors have been derived, and the degree of approximation of the values of the last column of Table III to those actually obtaining. To do this it is necessary to examine the distribution of potential between the three circular wires and the outer circular cylinder. It is probable that an exact solution of this problem has never been attempted, but a close approximation may be had by considering the potential due to three infinitely thin filaments located at the apexes of an equilateral triangle, each filament having the same and similar charge per unit of length. This case has been discussed very clearly and completely by Alexander Russell.[2] He shows that the equation of an equipotential surface due to the charges on the three filaments may be expressed by

$$r^6 - 2a^3r^3 \cos 3\theta + a^6 = r_1^2\, r_2^2\, r_3^2 = A^6 \qquad (1)$$

where r is the distance $O\,P$ from the center of the equilateral triangle to a point on the equipotential surface (see Fig. 15); θ is the angle which $O\,P$ makes with a line passing through O and one of the angular points of the triangle; a is the radius of the circle circumscribing the triangle; r_1, r_2 and r_3 are the distances of P from the three angular points; and A is a constant which contains the value of the potential of the particular surface in question. When A is zero the curves reduce to the three points α, β, γ. For small values of A the curves are ovals which approximate circles enclosing the three points. For large values of A the equation represents a single curve enclosing α, β and γ and which for increasing A approaches a circle.

By Greene's theorem we can replace any conductor by another surrounding it, provided that the surface of the outer conductor is an equipotential surface of the system of distribution. Consequently if we replace the three filaments by ovals coinciding with the nearer equipotential surfaces, and replace any one of the outlying continuous surfaces by a conductor, we have a system which approximates three cylindrical conductors in triangular arrangement at the center of an outer cylinder. If the approximation is sufficiently close we may use the relation of the exact case for calculating the potential gradients at the interesting points of the arrangement using the cylindrical conductors and outer cylinder. Russell does not discuss this question further than to note that when the longest radius of an outer surface is equal to $2a$ the variation from true

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[2] Russell, "Alternating Currents." Vol. 1, chapter IV.

circular form is less than 5 per cent. In the experiments described above, the greatest value of a was only one-sixth the radius of the outer cylinder. It may be shown by simple calculation that in the exact case the surface which passes through the point $r = 6a, \theta = 0$, has $6a$ and $5.99a$ as its maximum and minimum values of r. Consequently the error in the use of a true cylinder for the outer conductor is only a small fraction of one per cent, *i.e.*, negligible.

The maximum values of potential gradient in the exact case as well as in the case of three cylinders will occur at the extreme outer points of the three conductors, *i.e.*, at the outer intersection of a line drawn through the center of the triangle and the center of a wire section, with the circle or oval representing this section. The value of this potential gradient will vary with the length of sides of the triangle, that is, with the separation of the three wires. For the exact case the gradient at these points may be calculated as follows: The conductors are equipotential surfaces; if their potential be v_1, the surfaces are given by

$$v_1 = C - \frac{q}{3} \log \left(r^6 - 2a^3 r^3 \cos 3\theta + a^6\right) \qquad (2)$$

in which C is a constant and $\frac{q}{3}$ is the charge on each of the three wires per unit of length. The value of $\frac{q}{3}$ corresponding to a potential v_1 of the three inner conductors and v_2 of an outer enclosing cylindrical conductor of radius R is given by

$$\frac{q}{3} = \frac{v_1 - v_2}{2 \log \dfrac{R^3 - a^3}{a^3 - b^3}}$$

since the capacity[3] per unit length between the three wires in parallel and the outer cylinder is

$$K = \frac{3}{2 \log \dfrac{R^3 - a^3}{a^3 - b^3}}$$

At the point C, $\theta = 0$ and r is perpendicular to all the equipotential surfaces. Therefore the maximum normal surface potential gradient is given by

$$\frac{\partial v_1}{\partial r} = \frac{q}{3} \, \frac{6 r^5 - 6a^3 r^2 \cos 3\theta}{r^6 - 2a^3 r^3 \cos 3\theta + a^6} \qquad (3)$$

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[3] Russell, loc. cit.

In the experiments the outer cylinder was connected to earth. Thus the maximum normal surface intensity in volts per centimeter, which occurs at the points $r = c$, $\theta = 0$, is given by:

$$X = \frac{d\,v}{d\,r} = \frac{V}{2 \log \dfrac{R^3 - a^3}{a^3 - b^3}} \cdot \frac{6c^5 - 6a^3\,c^2}{c - 2a^3\,c^3 + a^6} \qquad (4)$$

in which V is the maximum value of the voltage between the outer cylinder and the three wires.

All of the above relations are deduced for the exact case in which the three inner conductors have their cross-sections of the oval shape shown in Fig. 15. Since the experiments were made with round conductors it is necessary to consider how closely the intensity as calculated by formula (4) will represent that occurring in the experiments. The nearest approximation to the exact case is that of round conductors which exactly enclose the ovals and which therefore have the diameter BC. A comparison of the radius of curvature of the oval at the points C, and the angle $2\,\theta$ subtended at the center of the triangle by the two tangents to the oval, with the corresponding quantities for the circle, will give an idea of the degree of approximation. Both these quantities obviously are a measure of the rapidity

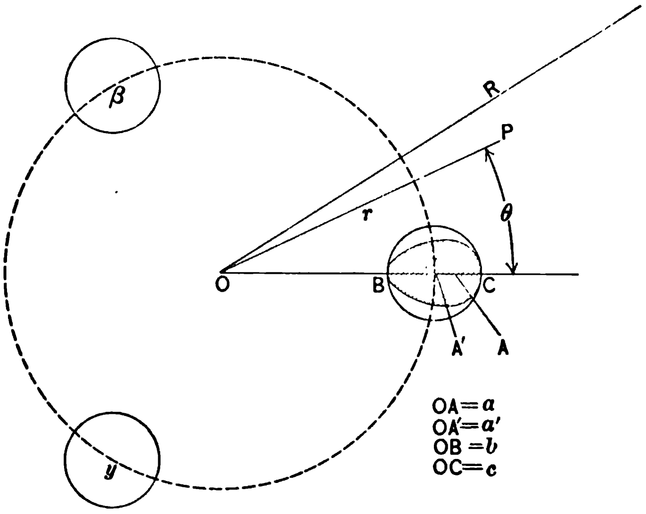

Fig. 15

with which the maximum electric intensity at the extreme outer point will vary with the distance from that point along the surface.

Both the radius of curvature ρ at the point C and the angle 2θ, between the two tangents to the oval from the center, may be calculated from the equations of the curves by well-known methods and are given by

$$\rho = c\,\frac{(c^3 - a^3)}{c^3 + 2a^3} \text{ and } \cos^2 3\,\theta = \frac{b^3\,(2a^3 - b^3)}{a^6}$$

in which *a* is the *a* of the formulas for the exact case and is the distance from the center of the system to each of the three points which are the origin of the true system of equipotential surfaces of which the ovals are a particular example. Thus *a* is greater than *a′*, the distance from the center of the triangle to the centers of the three circles which take the place of the ovals.

TABLE V

a' in.	a' cm.	ρ oval cm.	ρ circle cm.	$2\,\theta$ oval	$2\,\theta$ circle
0.125	0.317	0.943	0.119	37°16′	44°
0.1875	0.476	0.1048	0.119	27°50′	29°
0.25	0.634	0.1096	0.119	20°33′	21°37′
0.375	0.952	0.1158	0.119	14°4′	14°24′
0.5	1.27	0.1162	0.119		
0.625	1.586	0.1165	0.119	8°24′	8°36′
0.75	1.905	0.1176	0.119		
1	2.54	0.1178	0.119		

In Table V values of ρ and 2θ for circular wires of 0.119 cm. radius are compared with those for the true ovals which the circles are assumed to replace. The table shows that the values of both ρ and $2\,\theta$ for the oval and the circle differ by very small amounts when the distance of the center of the wire from the center of the system is greater than 0.63 cm. The values of the multiplying factors of Table III have been calculated from formula (4); the value of *a*, the true center of the exact system of ovals, may be readily obtained from the radius *a′* of the circle on which the centers of round wires lie, and the radius of the wires.

Since the values of ρ and $2\,\theta$ above are greater for the round wires than for the ovals, the values of the surface intensities for a given voltage will be less than in the exact case. Consequently the values given in Table III are too high, particularly for the small triangles. It does not appear, however, that this error is great enough to preclude the conclusion that the critical intensity for the three-wire arrangement is much higher for small triangles than that for one of the component wires alone; that with increasing radius of triangle the critical intensity decreases to the value pertaining to the size of the single wires; and that with further increase of separation the critical intensity appears to increase again. It appears from these results that the distribution of the electric intensity is the vital factor in the relation which obtains between the radius of a conductor and the critical electric intensity. Surface layers and condensation layers of high electric strength, often mentioned in vague terms to explain this interesting relation, have not the slightest foundation of experimental evidence. If, however, the theory of secondary ionization is to account for the facts it must show that in the converging field either the mean free path of the electron is shortened or that in some manner the gradient is less than that calculated from the geometrical configuration of the opposite conductors.

The principal results of this paper may be summarized as follows:

1. In the early stages of corona the carriers constituting the leakage current have the positive sign; with increasing voltage negative carriers predominate. Other peculiarities of the ionization arising from the corona are described.

2. The variation of the diameter of the corona with the voltage has been shown by photographic methods.

3. By dividing a circular conductor into three or more equal circular ones symmetrically placed the critical voltage may be raised 16 per cent for division into three, and 20 per cent for division into four wires. In these arrangements the maximum critical intensity for air is shown to have different values even though obtained at the surface of the same wire.

DISCUSSION ON "CORONA LOSSES BETWEEN WIRES AT HIGH VOLTAGES" (HARDING), "THE LAW OF CORONA AND THE DIELECTRIC STRENGTH OF AIR—II" (PEEK), AND "THE ELECTRIC STRENGTH OF AIR—III" (WHITEHEAD), BOSTON, MASS., JUNE 25, 1912.

John B. Taylor: Toward the end of Mr. Peek's paper he speaks of the mechanical vibration of wires. The photographs reproduced in his paper, Fig. 41 and 42, I think are easily enough explained, that is, the wire is pulled first on one side, and then on the other, by electrostatic forces, and if the wire is approximately attuned to the frequency, closely enough so that it can be made to vibrate with that frequency, you have this characteristic of negative on one side and positive on the other. Mr. Peek speaks of the vibration noticed on a pair of 20-mil steel conductors, 500 ft. (152 m.) long, strung at 10-ft. (3-m.) spacing, which I think must have been due to something of that condition.

I saw that myself one evening. We were out to take some photographs, but on putting the voltage on, the wire would begin to sway, and after a while it swayed so much that the particular photographs we were after could not be taken, although we got some interesting photographs of this swaying. It was at first supposed it was due to some vibration of the towers, as we were pretty close to the towers, but on taking the voltage off it was found that the swaying stopped. On five or six different occasions the voltage was put on, and the wires began to swing at a slow period of about sixty swings a minute. Obviously, the 60-cycle attractions could not have had anything to do with this wire swinging in a one-second period, and just exactly what caused it is still a mystery, although my own opinion is that there was something on the power line, which was supplied by the circuit at that time, which caused a small variation in the voltage, which variation happened to fall in synchronism with the period of the wire, as it happened to be on that particular day.

I do not know whether that has been observed on other occasions, but it seemed to me that the only way to explain the small vibration was that there was a small variation in the voltage of the circuit, which fell in with the period of the wire, although the voltmeters do not show any indication of the cause of such vibration. I had a suspicion that it was due to an air transformer, or some similar apparatus, on the same line, which called for a little more current than was normally running on the line.

In both of these papers we have a line of investigation somewhat different from the early corona papers, different from the subjects and particular lines of investigations which were taken up in those papers. Most of the early investigators, I think, tried to get limiting values on which to plot the curves. Of course, that is in order to determine the loss, but I think investigations like these are sooner or later going to show us a lot more about the real inherent nature of the corona, and, as in everything else, when we know just a little more about the whys and wherefores of it, we will be in a position to get around the limitations and reduce the losses.

These observations are very interesting, and I think it is next in order to combine the quartz lens with the stroboscope, in fact, to use all the tools which are available to any scientific investigator, when you want to get right down to the things which are either too quick or too small to see, but are in any event beyond the range of our normal senses.

A. E. Kennelly: The very interesting and important papers on corona this year have apparently reached a stage further than we reached last year.

It seems now to be really agreed that the corona and power loss becomes a parabolic law, which goes up as the square above a certain critical voltage, and the interesting points presented here, outside of the confirmation of that law, are as to what may be the scientific characteristics of the phenomena rather than the practical characteristics.

In the first paper of Professor Ryan, it appeared, according to his observations, that the increase in gradient on very small wires was inversely proportional to the radius, that is to say, the visible gradient was 30 kv. per cm., plus 10 divided by the radius, that is to say, a hyperbolic formula, approximately, over a considerable range in his observations.

As I understood it from Mr. Peek's results, his recent observations do not show that formula, but 30 plus q over the square root of the radius.

Another interesting feature of Mr. Peek's paper is his use of the stroboscope in obtaining pictures of wire in corona. Now I understand why we may have a physical basis for saying that electricity is red or blue, and having one conductor painted red and another blue—although the red in this case is negative and blue the positive. This is the reverse of the ordinary convention, but at last we have a physical basis for the color. Is it to be supposed that the blue is due to the more active operation of negative ions and the red due to the heat produced by the heavier positive ions, or is there any explanation for this difference in color?

Mention is made in Mr. Peek's paper that the appearance of the phenomenon is as though the blue electricity was streaming out from the positive wire into the surrounding space and received into the negative wire, as though the electricity was streaming out of the positive wire, and going into the negative wire, the kind of phenomenon we have in an electric current. Is it not possible that the phenomenon witnessed in the stroboscope may be called for by the negative electricity passing out of the air and then streaming into the positive wire? There is nothing in the stroboscopic picture to show whether the flow which appears to take place is projected outward from the positive wire into the air, or from the air into the wire, and a few words on that point would be very interesting.

In regard to Mr. Harding's paper, it is interesting to see the agreement of his observations with those given by Mr. Peek, and one of the great values of Mr. Peek's paper last year was the perfect clearness of his formulas. There was no doubt as to what they meant. Attached to each formula was the unit in which it was written, and attached to each symbol was the meaning of such symbol, and we owe him thanks for that clearness and attention to detail. I think the great progress made this year is partly attributable to that fact.

The agreement reached by Mr. Harding and Mr. Peek is very interesting. I would like to get Mr. Harding's opinion as to whether the large correction for the rack is not a little dangerous. Would not it be safer to experiment with a smaller correction of this kind, to have a larger line and shorter racks, so as to have a small correction to subtract from the actual observed losses?

C. P. Steinmetz: I wish to say a few words first on Mr. Harding's paper, in reference to one conclusion contained in it, and that is the quadratic law *below the critical limit.* These laws have first been derived as empirical laws. However, even an empirical law cannot be accepted as an approximation, unless it appears rational in its application. If you look at the curve of the quadratic law *above the critical limit,* you see that it points to a definite zero value at 30 kv. per cm. as the disruptive gradient, and is rational. But the quadratic law below the critical limit gives values which become negative at the higher spacing. This would lead to the conclusion that at the highest spacing, corona begins below zero, that is, it is there already at zero voltage, which obviously is not the case. In this case, therefore, it seems merely accidental that the points lie on an approximate quadratic curve, or rather that the quadratic curve is an approximation of some actual curve.

Mr. Peek's data a year ago did not give this quadratic curve, for losses near the critical voltage due to irregularity, but seemed to be best represented by an exponential curve. If you will look at this exponential curve, which contains the square of the voltage in the exponent, you will find that the first approximation of it will be the quadratic. However, the exponential curve would be only very approximate, because, while as the probability curve it is rational in applying to the irregularities on the conductor, it would only apply to those irregularities which are entirely irregular, but if there was some regularity in the irregularity, as, for instance, a ridge in the conductor, then there would be some regular arrangement which would disagree with the probability curve and give a quadratic curve of different constant.

The two other papers, those of Mr. Peek and Mr. Whitehead, continue the investigations of last year, to a considerable extent, mainly with the object of extending the range of application of the formulas given in the papers of last year. The papers of this year cover a wider range, and give a rationalization of these formulas, that is, they begin to give the theoretical and physical reasons why these formulas apply. The most interesting part is that these papers first give the separation of the alternating-current corona into two parts, the positive corona and the negative corona—Mr.Peek by photograph, by means of the stroboscope, and Dr. Whitehead by means of ionization. This is extremely interesting. As the positive and negative coronas are different, it appears probable that they also begin at different voltages, and, furthermore, that the losses at the positive and negative coronas are different. Now, look at what that means in engineering. It would mean, if the losses at positive and negative coronas are different, that there would be, if the line were perfectly insulated, a unidirectional electrification on the line which would increase until the potential difference of the negative against ground would be so much higher than the positive against ground that it would make the losses of the two equal.

There is mention made in the paper of a number of phenomena which show under certain conditions. There is a difference in the energy discharge in the air from the positive and negative coronas, and there would, therefore, be electrification on the line which should appear. It would mean, however, that if you could artificially produce the counter-electrification, by connecting unidirectional potential between line and ground, you should be able to extend the operating voltage, though possibly by a negligible amount only, before the corona losses appear. You see it is a very interesting field which is opened up here.

I want to refer to one point more, regarding the statement made by Dr. Whitehead, that there is no evidence that the free ionization of the air has any effect on the corona and that there is no such effect. I do not believe there has been any test made, or any evidence given of such a nature, under such conditions that an effect of the free ionization of the air should be expected. Whether the free ionization of air is great or small, as long as there are any free ions at all the corona should appear at the same voltage, at the same potential gradient. The only difference which the free ionization would make, or the only effect which it could have, would be rather in the rapidity with which the corona appears, in the time required to produce the corona. This free ionization of air could have an effect only on the transient corona, but not on the corona under permanent conditions, as in alternating circuit, where the free ionization of the air with which the corona at each half-wave starts is by necessity the same as the residual ionization of the preceding half-wave. So, there is no evidence thus far brought forward that the free ionization of the air has no effect upon the appearance of the corona, and it would be interesting to take that matter up and make a thorough investigation.

C. Francis Harding: We have two distinct types of papers before us. My paper did not attempt to go into the causes of the phenomena, but simply to point out how very easily and correctly Mr. Peek's results can be applied to practical transmission line design, and I want to second Dr. Kennelly's congratulations to Mr. Peek for presenting his data in such form, particularly the formulas, that engineers in designing high-tension transmission lines can readily predict, with sufficient accuracy for practical purposes, the probable corona loss, and therefore the necessary spacing and size of cables to avoid such loss.

With regard to Dr. Kennelly's suggestions in reference to the large rack losses, I wish to point out one feature in the paper, namely, that the greater portion of these losses represented by the lower dotted curves are not on the rack itself, but on the lines connecting the transformer to the experimental transmission line, and were therefore largely corona losses on wires, although obeying some different law, possibly, than the corona losses on the transmission line itself, which could be controlled. I think if the feeder loss could have been reduced it would have been advisable to have done so. However, as I stated, the two dotted-line curves are not quadratics, and the curves which are expressed in the full lines, representing a subtraction of the other two curves, are quadratics, the points falling very accurately on the curves. It seems to me, therefore, that we are getting very satisfactory results by that method, even though the subtracted loss is relatively large.

With regard to the suggestion of Dr. Steinmetz, this result, of course, is an empirical one, as he states, and the empirical data seemed to fall on a quadratic curve below, as well as above, the critical voltage, in this particular case. That does not mean, of course, that they will fall on quadratic curves under other conditions. The law below the critical voltage is, however, of little interest to the practical designer of transmission lines, and more attention has been paid to the curve above the critical voltage by investigators than to the portion of the curve below that voltage. However, the wires used were new, perfectly smooth wires, direct from the factory, and that fact might have had something to do with the coincidence of the points with the quadratic curve below the critical voltage.

F. W. Peek, Jr.: From the formulas given in *The Law of Corona*—I, the corona characteristics of practical transmission lines can be accurately predetermined. While the present investigation is being carried on partly with the view of getting at the fundamentals of corona formation and loss, the engineering and practical side is always kept prominently in view. Many new practical data have been obtained, and it is hoped, also, that some steps forward have been made in the theoretical direction.

The stroboscopic study has brought forth many interesting questions. Dr. Steinmetz has pointed out one of these, that as the result of the different apparent starting points of corona at different halves of the wave the line would probably be gradually increased in potential of a given sign against earth.

Referring to Dr. Kennelly's discussion: The formula for gradient is

$$g_v = 30\,\delta\left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right)$$

The other formula is not for corona starting point, but for apparent gradient, g_s, at spark-over. It is true the stroboscopic photographs do not show the "direction of flow;" one is simply given the impression, especially in the case of the point discharge, of, for instance, a steam jet discharging at the positive toward the negative. The statement is made rather as to the appearance in a descriptive or visual sense. More data on the direction of flow, etc., have been obtained, but are not as yet in form for publication.

In Mr. Harding's paper, it is very interesting to see that his results, on the whole, check so well my formulas of last year. There are one or two points with which I can hardly agree. One of them concerns the accuracy of the method of power and voltage measurement advocated by Mr. Harding. With a well designed transformer and exploring coil we found by actual test that the voltage as indicated by the coil is extremely accurate. Watts measured on the high side also always checked with watts measured on the low side when corrections were made for transformer loss. The spark gap is not suitable for voltage measurements of this sort, as there is a variation from day to day of as much as 15 per cent. If the exploring coil is not so placed in the transformer that it will measure the voltage correctly, it will not indicate the power factor correctly on the oscillograms. Thus by this spark gap-power factor method there are two chances of considerable error. Besides accuracy, the wattmeter method has the advantage of making a great number of readings possible in a short time. The $\Sigma\,\Delta$ method of reduction of data is not especially applicable unless a considerable number of readings is used.

It is generally difficult to make exact comparisons of loss as calculated by the formulas and loss measured on operating lines, because in most of these measurements all of the conditions are not given, such as variation of altitude along line, voltage rise at no load, temperature, etc. For instance, unless the effect of voltage rise along the line at no load is taken into account the measurements will show higher loss than the formulas. When these variables are considered as closely as possible the check is quite remarkable, as shown in Figs. 1 and 2, which give a comparison of curves calculated from formulas and readings taken by other investigators. The agreement would probably have been more exact if all conditions, such as temperature at different points of the line, etc., were exactly known. A very interesting check of the formulas is also given in a paper by Faccioli[1] before the N. E. L. A. on measurements of the 140,000-volt line of the Au Sable Electric Company.

Dr. Whitehead has in his paper brought forth, as usual, some ingenious new experiments. I refer especially to the section on "The Ionization Due to the Corona." Such work as this adds greatly to our knowledge of the mechanism of the breakdown of air under dielectric stress. The stroboscopic photographs which I have shown, as far as the investigations overlap, indicate much the same general results, such as different starting voltage of positive and negative coronas, etc. The stroboscopic photographs show a decided difference in the appearance of

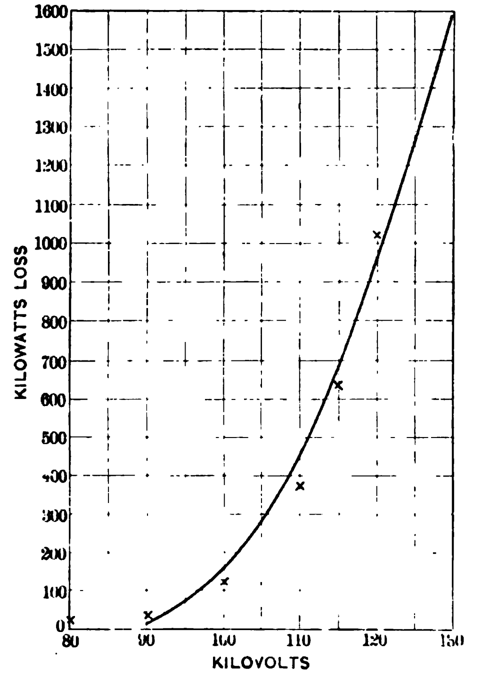

Fig. 1—Comparison of Calculated and Measured Losses

The x points are measured values. The drawn curve is calculated from the corona formula:

$$p = \frac{k'}{\delta} f \sqrt{\frac{r}{S}} \left(e - g_0 \, m_0 \, r \, \delta \; 2.302 \; \log_{10} \frac{S}{r} \right)^2 10^{-5}$$

Diam. of wire 0.375 in. (No. 0 cable), spacing 124 in., three-phase, length of line 63.5 miles.

Note—Test by Faccioli on corona losses, Shoshone-Leadville transmission line. Tests made on operating line three-phase, and at high altitude. Check interesting because of the number of variables taken into account.

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[1] "Corona in High-Tension Lines"—N. E. L. A. *Proceedings*, June, 1912.

corona on the positive and negative part of the wave. Further interesting data have been obtained as a result of the stroboscopic study, but are not at the present time available for publication.

The manner in which the air density factor enters into the expression for visual gradient was predicted long before experimental data over a great range of δ were obtained. The formula must take the form given if the energy theory of disruption brought out in *The Law of Corona*—I is true. This is further discussed in *The Law of Corona*—II. The observed results in Tables I and II follow this law, but the data range is not great as Dr. Whitehead states. Other data further confirming this law were given in the data appendix to this paper, which appendix was not printed. In the table here given, δ is taken over a very great range. The check of the law is apparent without further discussion.

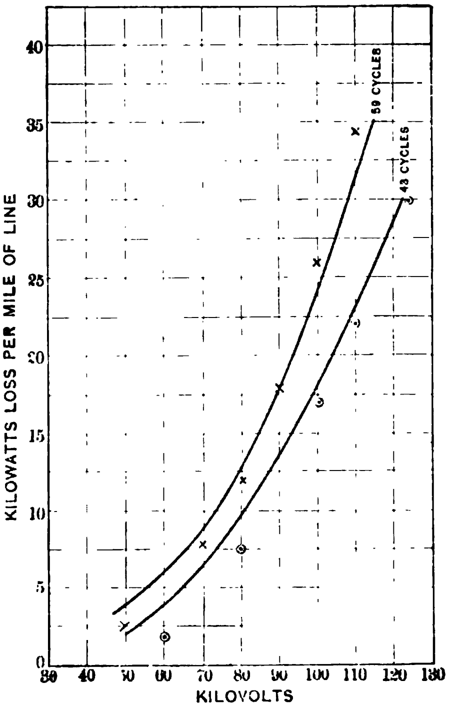

FIG. 2—COMPARISON OF CALCULATED AND MEASURED LOSSES

The x and 0 points are measured values. The drawn curves are calculated from the corona formula (see Fig. 1.) Diameter of wire 0.064 in., spacing 48 in.

Note—Tests made on short line by A. B. Hendricks, 1903-1904. This shows check at two frequencies.

δ	g_v observed kv./cm.	g_v calculated from formula $g_v = 31\,\delta\left(1+\frac{0.301}{\sqrt{\delta\,r}}\right)$
0.023	3.3	3.47
0.074	7.2	7.33
0.116	9.7	9.90
0.216	15.5	15.30
0.38	23.7	23.20
0.513	30.0	29.1
0.667	36.8	36.0
0.83	43.0	42.7
1.02	50.9	50.3

Radius of wire 0.254 cm.

J. B. Whitehead: Mr. Peek has performed a most important service in carrying out his experiments on the influence of temperature on the starting of corona. This is a line of work which has been very much needed ever since we have been studying this phenomenon. With the facility which characterized his earlier paper, Mr. Peek has converted his various results into formulas, thus proposing several interesting laws. In discussing the effect of the variation of the density of air on the critical electric intensity, Mr. Peek states that his results are explained if the density factor enters in both numerator and denominator of the expression for the critical intensity. Now, the results as plotted in the curves of the paper do not, I think, bear out that conclusion. If the density factor is used only as multiplying factor and stricken out of the denominator, you will get a curve which is as good as Mr. Peek's curve for the results given in the first table. The agreement is not, however, quite so good for Table II. But it should be noted that the real test of the formula lies in observations at low density where the curve departs from a straight line, and Mr. Peek has no observations in this region. I have discussed this with him and he tells me that many of the results have been stricken from the original paper by the Institute owing to limited publication space. It is very desirable indeed that in the proposal of a law so important as this, all the results should be given, and I hope that they may be obtained and published at some later time. To my mind they are more important than the development of the formulas expressing the results of sparking distances between water- and oil-covered wires. The conditions under which oil and water occur on the surface of wires are so varied and irregular, that it is questionable whether an empirical law will prove of any particular value.

I believe, however, that the downward trend of the curves of Fig. 4 at low densities is correct. We have just completed some investigations in our laboratory, which will soon be in print, in which we have carried the pressures much further down than those described in my earlier papers and those reached in Mr.

Peek's Fig. 4. We have shown, without question, the downward bend of the curves. The lines are nearly straight at values of density above one-half an atmosphere, making it very difficult, indeed, to predicate the law unless the pressure is reduced well below this value.

Dr. Steinmetz has made a suggestion in the language of the ionization theory in possible explanation of the larger values of intensity at which corona starts on small wires. I hope this indicates a greater sympathy with this theory than he has shown in the past. It is now widely accepted by physicists and undoubtedly offers better prospect than any other of an explanation of corona phenomena. He has, however, given the impression that my paper states that the presence of natural ionization in the air has an influence on the starting of corona. It must be evident to anybody who has considered the theory of secondary ionization that free ionization as it occurs in the air can never have anything to do with the starting of corona. Every comment I have made, and every experiment I have undertaken, has indicated that free ionization in the air has nothing to do with it. This fact is emphasized in the present paper because within the last year a paper has been presented before the Institute and discussed, in which it was maintained that free ionization has influence on the starting of corona.

A. S. Langsdorf (by letter): Mr. Peek's interesting and valuable paper has additional interest to the writer because the stroboscopic examination of the corona so fully described has anticipated a similar experimental study which he had planned. The idea that such a study might shed light upon the nature of corona formation around conductors subjected to alternating e.m.fs. was first suggested to the writer by an extended experimental study made by Professor Francis E. Nipher of Washington University, the results of which have been published from time to time in the *Transactions* of the Academy of Science of St. Louis.[2] Inasmuch as the results of Professor Nipher's work are less well known to electrical engineers than their importance warrants, it seems desirable at this time to submit to the Institute a brief summary of that part of his work and conclusions which is of particular interest in connection with the present paper.

All of the work referred to has been done with a large 8-plate influence machine, using discharge terminals of various kinds, but mainly (so far as present purposes go) the usual spherical brass knobs. Viewing the discharge in a darkened room under steady operating conditions gave results equivalent to a stroboscopic examination of an alternating electric field with a fixed setting of the stroboscope. It is interesting to state that Mr. Peek's photographs are in exact accord with those published in Professor Nipher's papers.

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[2] *Transactions* Academy of Science of St. Louis, Vol. XIX, Nos. 1 and 4; Vol. XX, No. 1; Vol. XXI, No. 3.

A long series of experiments involving the study of positive and negative discharges on photographic plates, which yielded many beautiful figures somewhat similar to the familiar Lichtenberg dust figures, taken in conjunction with other significant results, led Professor Nipher to the conclusion that the chief factor in all the phenomena involved is the negatively charged electron, and that the so-called positive ion consists merely of an atom that has been deprived of its normal store of electrons. This view is essentially the " one-fluid " theory of electricity. The figure traced on a photographic plate by a positive discharge always shows a characteristic tree-like pattern branching out from the positive terminal; *or* (and herein lies the key to the problem) it resembles much more the map of a river and its tributaries *draining into* the positive terminal. On the other hand, the figure produced on a sensitized plate by a negative discharge has a characteristic fan shape which leads irresistibly to the idea of a pressure discharge from the negative terminal. Looked at in this way, the influence machine takes on the aspect of a pump whose negative terminal is in a state of compression and whose positive terminal is in a state of rarefaction. This view, to the writer's mind, is much more illuminating than the common one of a double discharge, positive and negative.

Thus, imagine that the knobs of an influence machine, placed in a darkened room, are fully charged, the voltage being high enough to start the corona but less than sufficient to cause a disruptive discharge. The negative terminal, on the side facing the positive, will be surrounded by a thin layer of reddish light; the positive will be the apparent starting point of a tuft of bluish light (the positive brush) reaching toward the negative. As the voltage is increased, thin white streamers flash through the positive brush, the latter lengthens, thereby shortening the Faraday dark space between it and the negative glow, until ultimately a spark passes. But before the final breakdown there are two distinct currents of air, one moving from the negative towards the positive, the other from the positive to the negative; this has been shown by means of a small windmill built entirely of mica and hard rubber. By the one-fluid theory this can be explained as follows: The air molecules in the immediate neighborhood of the positive terminal are partially drained of their negative electrons to supply the deficiency created by the " suction " of the electrical pump; they then become " positively " charged and are repelled. Colliding then with neutral molecules, ionization takes place and the more remote molecule hands on its negative charge to the one nearer the positive terminal. Electrons are then traveling toward the positive, while their carriers, the positive ions or air molecules, are moving the other way, much as a runner might jump from cake to cake of floating ice. The jostling of the air particles is then responsible for the light of the brush discharge. At the negative terminal, on the other hand, the negatively supercharged metal passes on to the surrounding air layer some of its electrons, which then travel across the dark space (the air acting as carrier) to supply the deficiency at the positive end. In the dark space the air particles do not have the to-and-fro motion above referred to, hence there are no collisions and no light.

It is commonly believed that the formation of the positive brush in a direction from positive to negative is an evidence of a true positive discharge, instead of a negative discharge in the opposite direction as described above. But Professor Nipher points out that this observed motion, whose rate of propagation (in a long exhausted tube) has been found by Sir J. J. Thomson to be of the order of that of light, may be only an optical illusion; for instance, if the rate of recession of Niagara Falls were extremely great, the river would appear to move up-stream, whereas the real flow is actually the other way.

This theory of a negative " compression " and a positive " rarefaction " satisfactorily explains a number of other observed phenomena. Thus, if the discharge knobs of a machine are set so that disruptive discharges pass freely between them, the introduction of a large sheet of copper between the knobs, and at or near the positive, will immediately suppress the sparking, whereas the same sheet placed at or near the negative will have no effect whatever. Since the average potential gradient is the same in both cases, this fact apparently points to the formation of corona at different potentials at the two terminals, the negative requiring the higher potential.

Corroborative evidence of the suction effect at the positive terminal is furnished by any Geissler tube having a twisted form. The positive glow readily finds its way through all the intricacies of the tube in a way that is strikingly different from the obvious pressure discharge of a cathode stream, as in a Braun tube. Again, an X-ray tube with grounded anode and with its cathode connected to the negative terminal of a machine whose positive terminal is grounded, will work satisfactorily, whereas it will not work, or only fitfully, if its cathode is connected to the positive, the negative end of the machine being grounded; but if the cathode of the tube is grounded and the anode is connected to the positive terminal, the results are as good as in the first case. In this connection the interesting suggestion has been made that the difference between positive and negative discharges in medical therapeutics may bear the same relation to each other as do cold and hot applications.

It is interesting to note that Mr. Peek's conclusions can be brought into accordance with the above theory by interchanging the words " positive " and " negative " in the sentence near the end of Section X—" Stroboscopic Study of Corona " in Mr. Peek's paper (page 1091). This sentence would then read:

" The stroboscopic study *suggests* that the corona loss is, in effect, in the form of a ' conduction ' across from negative to positive, always starting from the negative conductor—thus starting alternately at each half cycle, first from one conductor, then from the other."

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 25, 1912.

ELECTROLYTIC CORROSION OF IRON BY DIRECT CURRENT IN STREET SOIL

BY ALBERT F. GANZ

The electrolytic corrosion of iron when exposed to an electric current leaving the iron in damp soil has already received a great deal of attention and is a matter of very great practical importance. Stray currents from direct-current electric railway systems employing the running tracks as return conductors frequently reach underground piping systems and cause corrosion by electrolysis. There has been some question as to whether or not the weight of iron oxidized or destroyed under the conditions existing on underground structures is equal to that calculated from Faraday's law, on the basis of 1.044 grams of iron destroyed by one ampere-hour, and whether various kinds of iron are corroded at the same rate with the same amount of current leaving the iron to pass to damp soil; and certain classes of iron have been claimed to resist electrolytic corrosion. Some have also believed that with very low current densities the amount of corrosion produced is less than the theoretical amount.

It has been shown that under some laboratory conditions iron assumes a passive state where the actual amount of corrosion produced is less than that calculated by Faraday's law, but it has not been shown that such conditions exist in the case of underground structures buried in street soils. The subject of electrolytic corrosion of iron is, however, so large and there are so many possible variations that a complete investigation covering every possible phase of the subject is impracticable in any one series of tests. In a recent paper,[1] Mr. J. L. R.

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[1] "Electrolytic Corrosion of Iron by Direct Current", by J. L. R. Hayden, *Journal of the Franklin Institute*, October, 1911.

Hayden describes some laboratory experiments dealing admirably with the problem of the electrolytic corrosion of iron in various laboratory solutions when subjected to large current densities. The current densities used by Mr. Hayden ranged from 0.21 ampere per sq. ft. (2.25 amperes per sq. m.) to 3.35 amperes per sq. ft. (36 amperes per sq. m.). Mr. Hayden found that with a number of electrolytes, particularly with certain nitrates and with bichromates, much smaller amounts of corrosion were produced than the theoretical amount. In all of these cases, however, the greatest deviation from Faraday's law was found with the largest current densities. With chlorides and sulphates Mr. Hayden always found an amount of corrosion corresponding to the theoretical value. As Mr. Hayden has pointed out in the paper, his tests were made with laboratory solutions and not with street soils. The lowest current densities used by Mr. Hayden are also from 10 to 100 times greater than the densities with which currents are found in practise leaving underground structures. The tests described in Mr. Hayden's paper, while exceedingly valuable, do not therefore necessarily warrant any conclusion as to what will happen to pipes buried in street soils when subjected to stray electric currents.

The experiments described in the present paper were particularly designed to determine the relative rates of corrosion of various kinds of iron in two typical kinds of street soil, when subjected to such low current densities as are ordinarily found in practise on underground structures. Four sets of tests were made, each extending throughout 47 days, to determine the rates of corrosion of commercial steel, commercial wrought iron, ingot iron, and cast iron, and to compare the actual amount of corrosion with that calculated by Faraday's law. It was attempted in these tests to approach practical conditions as nearly as possible. The tests were conducted in the electrical laboratory of Stevens Institute of Technology, and the detailed results are given in the following:

GENERAL DATA

Two kinds of soil were used in the tests, which were obtained from street excavations near gas mains in Long Island City. One of these excavations was chosen where the soil appeared to be largely light sand mixed with some clay, and the second was chosen where the soil was heavy and dark and appeared to be a mixture of clay and loam. Several barrels of soil from each excavation were obtained for these tests. To assure uniformity of soil conditions all of the soil of each kind was passed through a fine mesh sieve and then thoroughly mixed in a large wooden box before being used in the tests.

For the samples of iron, standard 1¼-in. (3.175-cm.) pipes were chosen, such as are used ordinarily for service pipes, and these pipes were of commercial steel, commercial wrought iron and ingot iron, each test pipe being about 18 in. (45.72 cm.) long. The first two tests were conducted with these three kinds of iron pipe. For the third and fourth tests cast iron pipes of the same size were added.

The four sample pipes of each kind of iron used for the tests were placed in suitable test boxes. Each pipe was marked in the metal at one end with identifying numbers, and a hole was drilled and tapped at this end for convenient electrical connection. Two pipes of each kind were placed in clay and loam soil, and two pipes of each kind in clay and sand soil; one set of pipes was subjected to damp soil only, and the other set of pipes was subjected to damp soil and to an externally applied electric current.

Before the tests were begun each pipe was thoroughly cleaned in a manner to be described in greater detail later, and was then weighed by two independent observers on a physical balance which responds to 10 milligrams. At the end of each test each pipe was similarly cleaned and again weighed on the same balance by two observers. From the difference in the weighings before and after the test the loss of weight was determined. The difference between the loss of weight of any one pipe subjected to damp soil with external electric current and the loss of weight of the corresponding pipe subjected to the action of the same kind of soil but without external electric current was taken as the loss of weight due to electrolysis.

In the case of the pipes which were subjected to external electric current, the strength of this current was determined in every case both by means of copper voltameters placed in series with the pipes, and by means of a current-time curve plotted from indicating meter readings taken every few days throughout the test. In general the results obtained from the voltameters and from the current-time curves agreed quite well, and the average of the two values was taken as the total quantity of electricity passed.

Four separate tests, each of 47 days' duration, were made.

The general results of these tests are given in Table I. In the first and second tests all of the pipes which were to be subjected to external electric current were connected in parallel to a constant-voltage supply, while in the third and fourth tests the pipes were connected in series, thus producing the same current flow from each pipe to the surrounding soil. During all tests the test boxes were kept in one of the laboratory rooms. The detailed conditions and arrangements of each test are given below.

Test No. 1. The pipes as received from the manufacturer were cleaned with kerosene and benzol and wire-brushed to remove loose scale and rust. After having been thoroughly cleaned and dried they were placed in wooden test boxes. Four boxes were provided, each being approximately 12 in. by 12 in. by 12 in. (30. 48 cm. by 30.48 cm. by 30.48 cm.) inside dimensions, with three holes bored in each end through which the pipes projected. Three pipes, one of each kind of iron, were placed in each test box. A sheet of copper placed at the bottom and a piece of copper wire gauze placed on top served as ground plates. Two boxes containing clay and sand soil with three test pipes in each box, and two boxes containing clay and loam soil with three test pipes in each box, were set up with ground plates as above described. A storage battery, having a voltage of approximately 14 volts, was connected with its positive terminal to the pipes in two boxes, one with each kind of soil, and its negative terminal to the ground plates. In circuit with each of these pipes was placed a suitable copper voltameter. No external electromotive force was applied between pipes and ground plates in the remaining two boxes. During the test, 250 cu. cm. of hydrant water was added to each test box approximately every third day in order to keep the soil damp. In the case of the pipes subjected to external electricity, the current delivered to each pipe was measured practically every day by means of an ammeter inserted temporarily, and the voltage between pipes and ground plates was also measured. After the test had been continued in this way for 47 days the test pipes were removed from their boxes, washed in hot water to remove adhering soil, soaked in kerosene to soften the rust, wire-brushed until clean, then washed in benzol, dried and weighed as before.

Test No. 2. For test No. 2 the pipes were taken directly at the end of test No. 1 and replaced in their test boxes. The same boxes and the same soil and ground plates were used as in test No. 1. All conditions of test No. 2 were identical with those of test No. 1 except that a caustic potash battery was used to maintain the pipes 0.7 volt positive to the ground plates and 200 cu. cm. of hydrant water was added to each box practically every day, thus maintaining the soil in a damper condition than in test No. 1. At the end of 47 days the pipes were again removed, and cleaned and weighed in the same manner as after test No. 1.

Test No. 3. For test No. 3 the same pipes were used as received from test No. 2, with the addition of four cast iron pipes, which before being subjected to test were also cleaned with kerosene and benzol and then dried and weighed. In this test it was desired to subject each pipe to the same current instead of to the same voltage as in tests No. 1 and No. 2. For this reason 16 test boxes were constructed, each approximately 16 in. by 6 in. by 6 in. (40.6 cm. by 15 cm. by 15 cm.) internal dimensions, with one hole in each end through which the pipe projected, thus exposing 16 in. (40.6 cm.) of each test pipe to soil. The ground plate in each test box was placed at the two sides and the bottom and top of each box, thus completely surrounding the test pipe, the lower portion of the ground plate consisting of copper sheeting and the upper portion of copper wire gauze. The soil was obtained from the test boxes used in tests No. 1 and No. 2, each kind of soil being mixed thoroughly together with some additional soil of the same kind left over from the original shipment. Eight of the new test boxes were filled with clay and sand soil and eight with clay and loam soil, and one pipe was placed in each test box. Four boxes containing clay and sand soil, each containing a different kind of iron pipe, and four boxes containing clay and loam soil, each containing a different kind of iron pipe, were connected electrically in series—that is, the pipe in one box was connected to the ground plate of the next box. A potential difference of about 125 volts was maintained across the eight boxes by means of a storage battery. In this way the same current was made to flow from each pipe to the surrounding soil. In series with the circuit were placed two copper voltameters. The remaining eight boxes, four with each kind of soil, were left without electrical connections so that the pipes in them were subjected to damp soil only. During the test approximately 100 cu. cm. of hydrant water was added practically every day to each box, and the current in the circuit and the potential difference between pipe and ground plate in each box was measured every few days. At the end of 47 days each pipe was removed from its box, washed with hot water to remove the adhering soil, soaked in ammonium citrate to loosen and remove the rust, wire-brushed, then washed in naptha, dried and weighed. Ammonium citrate was used as it had been found by trial that this would more quickly and more effectively loosen rust than would kerosene or benzol.

Test No. 4. In order to eliminate all possible effects of previous corrosion, scale, etc., each test pipe was turned down in a lathe to bright metal, then cleaned with naptha, soaked in ammonium citrate, rinsed in water and naptha, then dried and weighed. The pipes were then replaced in their boxes and the test run practically in the same manner as test No. 3, except that 150 cu.cm. of hydrant water was added to each test box each day, thus maintaining the soil damper than in test No. 3, and that a recording milliammeter was kept in circuit. At the end of 47 days each pipe was removed and subjected to exactly the same cleaning processes as at the end of test No. 3. They were then dried and weighed as before.

RESULTS OF PHYSICAL EXAMINATION OF PIPES AFTER TESTS

The pipes which had been subjected to damp soil only, showed slight surface corrosion but no pitting after test No. 1 and test No. 2, and some slight pitting after test No. 3, but in no case was this pitting comparable in severity with that produced where an external electric current had been applied. After test No. 1 the coating of scale originally on the pipes was found practically intact, but it was found partly removed after test No. 2 and had almost completely disappeared after test No. 3, the scale then remaining being in well-defined patches which showed little corrosion. After test No. 4, where all scale had previously been removed the corrosion was extremely uniform, without the slightest evidence of pitting. It will be noted from Table I, in the column marked *B*, that these pipes in general showed an increasing loss in weight in the successive tests, with the exception of test No. 4, where the loss in weight was in general slightly less than that in test No. 3.

Pipes subjected to damp soil plus applied external electric current showed some evidence of pitting after the first test, the pits becoming more pronounced after tests No. 2 and No. 3. After test No. 4 the pitting was found quite as severe as after test No. 3. It

will be noticed also from the last column in Table I that the value of the ratio of the actual loss from electrolysis to the theoretical loss decreases in general in the successive tests, that is, as the scale is removed. Hence it would appear that with the exception of cast iron the scale does not protect pipes from electrolysis and may even aggravate it. It is also evident that localized corrosion resulting in pitting occurs even when all scale has been removed and a uniform metallic surface is exposed to the soil. In the case of cast iron the iron is oxidized by electrolysis but remains in place as a graphitic mass having little mechanical strength but retaining the surface in its original condition without exposing pits. This graphitic material is quite soft and can be easily dug out with a knife or other suitable tool.

Discussion of Results

The current-time curves for each test show a rapid falling off of the current during the first few days. As an example of this the following values of current are given from test No. 3:

At beginning of test	0.100	ampere.
At end of 1st day	0.050	"
" " " 2nd day	0.0298	"
" " " 5th day	0.0125	"
" " " 12th day	0.0072	"
" " " 19th day	0.0062	"
" " " 29th day	0.0050	"
" " " 47th day	0.0033	"

This indicates that the resistance increases very rapidly at first and then increases only very slowly. This increase in resistance was found to take place at the surface of the pipe or in the layer of soil immediately surrounding the pipe. This was determined by means of a separate test, in which, after the resistance had increased, the pipe was removed, wiped off with waste, and immediately replaced, when it was found that the resistance was again as low as at the beginning of the test.

The detailed results of the tests and of the calculations made from these results are given in Table I. In the fourth column of this table the average voltage between each test pipe and the ground plate is given in volts. In the first test each pipe was maintained at a constant positive potential of 14 volts, and the current produced by this voltage varied with each pipe, being determined by the accidental resistance of soil and of the surface contacts in each case. In the second test the pipes were maintained at a constant voltage of 0.69 volt, and the current from each pipe varied as before. In test No. 3 the pipes were all connected in series so that the current leaving each pipe was the same, but the voltage between each pipe and the ground plate now varied. It will be noted that this voltage ranged from 24.5 to 37.3 volts in the clay and sand soil, while in the clay and loam soil it was less than one volt. In test No. 4 the pipes were again connected in series, and the voltage in the clay and sand soil ranged from 15.4 to 26.3 volts, while in the clay and loam soil it ranged from 8.53 to 17.0 volts. While the applied voltage in tests No. 3 and No. 4 was the same, it will be noted that the average current in test No. 4 was over three times as large as in test No. 3.

Since the same soils were used in tests No. 3 and No. 4, this difference in current and in relative voltages, indicating changes in resistance, may be due to the fact that for test No. 4 the pipes were turned down to a smooth surface whereby better and more uniform contact was secured between pipes and soil.

The actual loss of weight of the pipes in the tests, as determined from the weighings made before and after the tests, is given in columns *A* and *B* of Table 1. The difference between the loss of weight of any pipe subjected to damp soil with applied electric current and the loss of weight of the corresponding pipe subjected only to damp soil is taken as the loss of weight due to electrolysis and is given in column *C*. The theoretical loss from electrolysis as calculated from the ampere-hours which passed from each pipe to the surrounding soil, and from the electrochemical equivalent of iron, namely 1.044 grams per ampere-hour, is given in column *D*. The actual total loss (column *A*) divided by the theoretical loss from electrolysis (column *D*) is given in the next to the last column marked $\frac{A}{D}$, and the approximate actual loss from electrolysis (column *C*) divided by the theoretical loss from electrolysis (column *D*) is given in the last column marked $\frac{C}{D}$.

It will be noted that in every case the actual total loss divided by the theoretical loss from electrolysis is greater than unity, and that the approximate actual loss from electrolysis divided by the theoretical loss from electrolysis, as given in the last column of Table I, is also greater than unity in every case but three, in which cases these values are 0.96, 0,95, and 0.88. As already stated, in the case of the cast iron pipes there is left as the result of electrolysis a soft graphitic material which is difficult to remove. The one low value of 0.88, obtained for cast iron in test No. 3, is therefore probably accounted for by the fact that this graphitic material had not all been removed.

An examination of the last column of the table shows that the actual loss from electrolysis divided by the theoretical loss was much larger in the first test than in the last test, particularly in the case of clay and sand soil. In one of these cases in the first test the actual loss of weight from electrolysis divided by the theoretical loss was as high as 5.3. This may be partly due to some scale having been loosened by corrosion of the metal and afterward brushed off in the cleaning of the pipes. It may be remarked, however, that after test No. 3 a physical examination of the pipes showed that those which had been subjected to the action of damp soil only appeared to have lost nearly as much of the original scale as those acted upon by electric current. It therefore does not seem likely that the large values of the ratios above mentioned are entirely due to loss of scale, but rather indicates that a great deal more than the theoretical amount of iron was lost by electrolysis.

It will be noted that the loss of weight by electrolysis appears to be absolutely independent of the applied voltage, except in so far as the voltage determines the amount of current produced, 0.7 volt being quite as effective in producing corrosion as 30 volts.

No chemical analyses of the soils used were made, except that a sample from each kind of soil was tested for chlorides and showed the presence of these salts.

CONCLUSIONS

The duration of these tests was not sufficiently long to warrant positive conclusions to be drawn regarding the relative corrosion of the four kinds of iron tested, when subjected only to the action of damp soil. The following conclusions appear, however, to be warranted:

The corrosion of iron by electrolysis in the two kinds of street soil tested is independent of the value of the applied voltage, except in so far as this determines the amount of current produced, and less than one volt can produce corrosion by electrolysis.

For the two kinds of street soils tested, and with current densities ranging from 1.7 milliamperes per sq. ft. (18.3 milliamperes per sq. m.) to 54 milliamperes per sq.. ft. (581 milliamperes per sq. m.), the loss of weight of iron by electrolysis is at least equal to that calculated by Faraday's law, and is in general greater than the theoretical loss. In all cases electrolysis tends to cause localized corrosion and decided pitting. Surface scale appears to accelerate corrosion from electrolysis with all irons except cast iron; this was especially pronounced in the case of the steel pipes tested. When the surface scale was removed there was practically no difference in the amount of corrosion produced by a given current leaving iron for damp soil between commercial steel, commercial wrought iron, ingot iron and cast iron.

It should be pointed out that the electrical resistivity of cast iron is about ten times as great as that of wrought iron, steel, or ingot iron, and the usual lead joints in cast iron pipes also have a resistance which is many times greater than the screw coupling joints usual with wrought iron and steel pipes. For these reasons a given voltage drop through ground will cause a much smaller current to flow on a cast iron pipe than on a wrought iron or a steel pipe, thus practically making cast iron pipes much less subject to electrolysis than wrought iron or steel pipes. It must also be noted that when a cast iron pipe is corroded by electrolysis, the iron is oxidized but remains in place as a graphitic mass having little mechanical strength, but possessing the ability to maintain the pipe gas-tight and sometimes even water-tight for considerable periods, while with wrought iron or steel pipes this does not occur, so that holes and consequent leaks are more quickly produced. Frequently where cast iron pipes appear to be immune from electrolysis because no evidences of leakage have developed, an examination of the pipes would reveal that a great deal of corrosion has actually taken place and that the pipes have been very greatly weakened.

The tests described in this paper are by no means considered complete. There are in fact so many possible variables, such as different kinds of soil, different degrees of wetting the soil, different kinds of iron, different voltages, different current densities, etc., that it would be extremely laborious to make a complete set of tests. The writer expects, however, to continue the experiments along the line outlined in this paper and hopes that the discussion will bring out suggestions which will serve to make the next series of tests more valuable.

DISCUSSION ON " ELECTROLYTIC CORROSION OF IRON BY DIRECT CURRENT IN STREET SOIL " (GANZ), BOSTON, MASS., JUNE 25, 1912.

Carl Hering: It seems to me that the tests made by Professor Ganz are very valuable, and we are fortunate to have had the benefit of his experience. But I think that to speak of voltage as Professor Ganz does in this paper, is somewhat misleading. The voltage for the electrolytic corrosion of iron is negative. Therefore it should be possible that with no external voltage at all there might be some corrosion. There are always two voltages, one at each electrode, and we generally refer to their sum, as it is difficult to separate them. The result described was perhaps due largely to " over-voltage " at the copper electrode which he used. In my opinion there is also an important mechanical effect in underground electrolysis in the form of the rate of diffusion of the liquid which does the electrolyzing. If that liquid cannot circulate rapidly there will be much less electrolysis than if it can, and it therefore seems to me that this effect of the circulation of the liquid through the soil is an important factor in determining whether the corrosion will be bad or not; it must also have a very decided effect on the voltage. Professor Ganz says nothing about the inside of the pipe and whether the results there are the same or not.

Edward B. Rosa: Regarding the excessive loss of weight by corrosion, it does not seem to me that it is necessary to assume that it is due to the removal of metal by mechanical means. At the Bureau of Standards we have made some similar experiments, and under some conditions the excess above the calculated value is considerable. It is well known that if iron pipes are embedded in cinders or in certain soils, the corrosion may be very greatly accelerated. I have known of one case where a line was laid through cinders and the pipe was destroyed within a year without the application of any outside current whatever. If the current puts the surface in a different condition from the surface of the pipe exposed as a blank experiment, the local action of self-corrosion may be thereby accelerated. These experiments are of great importance, and I think they emphasize the need of making laboratory experiments under as nearly as possible practical conditions.

Irving Langmuir: The corrosion of the pipe and the consequent loss in weight, in excess of that calculated by Faraday's law, must be due to oxidation. The iron in the ferric condition reacts with the iron itself to produce iron in the ferrous condition, thus causing a greater corrosion of the pipe. Some experiments made at Stevens Institute several years ago threw some light on the pitting. We placed two iron plates in the soil and passed a current between them for several days. At the end of that time we opened the circuit and found that there was a potential difference between the plates, in the same direction as the original current, thus tending to maintain the current.

Therefore, if the current leaves a pipe at one place with a little higher current density than at another, there will be a voltage set up at that place which will make the current concentrate at that point. The explanation of this is difficult to find. There are one or two other cases where a similar phenomenon is noticed. For example, the same effect may be observed with hydrochloric acid alone. If a current of very low density be passed between two platinum electrodes in a dilute solution of hydrochloric acid through which hydrogen is bubbling, it is found, upon opening the circuit, that there is a difference of potential between the electrodes in the same direction as that which originally produced the current. This effect, however, persists only a short time.

C. H. Sharp: The idea that I desire to express about the excess of corrosion over and above the theoretical amount, is that the action of the current accelerates the normal or so-called " chemical " oxidation of the iron. Consequently the ordinary oxidation goes on more rapidly when the current is flowing than when it is not. One interesting thing is Professor Ganz's suggestion as to the reason for the greater durability of cast iron pipes than wrought iron and steel pipes, explaining the fact on a rational basis. He did not say anything about scale or about surface conditions or anything like that, but he showed that the higher resistivity of cast iron alone would result in greater durability.

Albert F. Ganz: Dr. Hering has said that the voltage which I have measured in my experiments is somewhat misleading, because there are always two voltages, one at each electrode. This is, of course, true, but I was measuring the total applied voltage between the electrodes as we do when we make the usual potential survey. Regarding the insides of the pipes, I wish to say that in my experiments only the outside surfaces of the pipes were in contact with the soil, so that the inside surfaces were not affected by corrosion. Referring to Dr. Rosa's remarks, I wish to say that the large excess of corrosion over that calculated from Faraday's law, amounting to several hundred per cent in some cases, was undoubtedly due to the effects of scale on the surface of the pipes, because in the last series of experiments where this scale was removed by turning down the pipes before the test was begun, the excess of corrosion over that computed from Faraday's law was only from 3 to 23 per cent, and this excess of corrosion is probably due to the accelerated natural corrosion set up by the electrolytic action.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

THIRTY YEARS' PROGRESS IN THE ELECTRIC FURNACE

BY F. A. J. FITZGERALD

There has been so much written about the electric furnace since it entered into regular commercial use about 20 years ago that the presentation of a paper on the subject treating it in a general way is not apt to be interesting. But a promise to attempt the preparation of such a paper having been given, it was thought that there might be some interest attaching to a review of the development of some furnaces during the past 30 years. Moreover, it is often useful to look back over ground that has been covered in order to obtain suggestions as to the best direction to be taken in attempting further advances.

It is now 30 years since Sir William Siemens melted about 20 pounds of steel, as well as platinum, in notable quantities in an electric furnace with which he had been experimenting since 1878, and since then the electric furnace has so far developed that there are great numbers, both in Europe and this country, regularly engaged in the commercial manufacture of steel. While it is true that others had made some use of electrothermic methods at a much earlier day, for example Despretz, whose source of current was 600 Bunsen cells, yet Siemens's furnace must be considered the first really practical one, coming as it did after the invention of a cheap source of energy—the electric generator.

Siemens's work is of particular interest because he saw the possibility of using the electric furnace for steel manufacture, and, so far as the principles are concerned, they are the same as those in actual commercial use to-day. One of his furnaces was made of a graphite or other refractory crucible enclosed in a jacket of heat-insulating material. Inserted in the bottom of the crucible was an electrode of iron, platinum or carbon, while passing through the cover of the crucible was another electrode. The latter was connected to an automatic regulating device consisting of a solenoid, this serving to vary the length of the arc and thus keep the rate of generation of energy constant. In working the furnace the steel or other metal was introduced into the crucible and made contact with the lower electrode, while an arc was drawn between the upper electrode and the charge. In such a furnace Siemens melted steel in quantities of more than 20 pounds.

In another form of electric furnace devised by Siemens, the electrodes entered the crucible in a horizontal direction near the top and opposite one another so that an arc was formed between them and heated the charge below by radiation.

Siemens's work must be considered as the forerunner of at least two well-known kinds of electric steel furnaces which are in existence to-day in actual commercial use for the manufacture of steel, although he never was able to do commercial work with his apparatus because electrical engineering was not sufficiently advanced.

The growth of the Siemens electric furnace for steel making was at first slow, for numerous practical difficulties in its working had to be overcome, but so many of these have at last been met successfully by men like Heroult, Girod, Stassano and others who have modified the apparatus in various ways, that now we have furnaces like those of the Steel Corporation in Chicago and Worcester working on charges of 15 tons of steel.

Siemens in his furnace used direct current and laid particular stress on the point that the charge should be connected to the positive side of the circuit, since it is well known that in the electric arc it is at the positive electrode the main generation of heat occurs. In the modern furnaces, however, alternating currents are used for obvious reasons, and the surface of the molten bath is covered with a layer of slag which becomes intensely heated, not only by the arc but by the current which it carries. In this way ideal conditions are obtained for refining the metal, as the steel and the molten slag between which chemical reaction is desired are intensely heated at their surfaces of contact. Moreover, the slag effectually prevents the introduction of carbon from the electrodes into the metal. The problem of regulating the electrodes automatically has also been successfully worked out by means of the well-known Thury regulator, though it would seem that this could be simplified.

There were, of course, a large number of metallurgical problems to be worked out in connection with the steel furnace, but these have apparently been met successfully, and we finally have the electric furnace working alone commercially, or what is perhaps more generally important, acting as an auxiliary to fuel-heated furnaces. The most serious problems connected with furnaces of this type at the present time are those relating to electrodes and roofs. Some years ago when the electric furnace was working on a much smaller scale than is demanded to-day, the strongest argument advanced against it was that the cost of heating by means of an electric current must of necessity be so excessive that the idea was impracticable. That, however, is criticism seldom heard today, for it has been found that in actual practise the furnace can be so used that the question of cost of electrical energy is by no means of the first importance. On the other hand, little used to be said about electrode cost, but now that is a most vital question and is apt to enter into the total cost of working as a much larger item than power.

The manufacture of large carbon electrodes, say 20 in. (50.8 cm.) square and from 7 to 10 ft. (2.3 to 3.04 m.) long, is by no means easy, and even when they are successfully made in the electrode factory they may go to pieces in the furnace. Even if they do not break there is the problem of "butts." Suppose a large electric steel furnace with the roof three ft. (0.91 m.) away from the bath, then it is safe to say that when the electrode holder is lowered down and comes in contact with the roof of the furnace, there will be a carbon " butt " about four ft. long (1.22 m.) which must go in the scrap pile. Apparently this serious difficulty is going to be overcome by electrodes which can be fastened end to end so that they may be continuously fed into the furnace, and thus there will be no waste from " butts ". Within the last few months there has been a good deal of work done in this direction and the results are very promising. The electrodes are made with a circular cross-section instead of square and have threaded sockets in the ends so that by means of threaded plugs the electrodes may be fastened together and thus fed continuously into the furnace without any waste.

This, as has been said, is promising, but has the limit of the electric steel furnace been reached as regards size? Except as regards electrodes there is no reason to believe that it has, but the 15-ton furnaces working now, need electrodes about 20 in. (50.8 cm.) in diameter, and if the size is doubled and the general design is kept the same, electrodes 27 or 28 in. (68.5 or 71.1 cm.) in diameter will be required. Perhaps these can be made and can be used continuously as described above, but the writer believes that development in this direction is a mistake, and that far better results can be obtained by multiplying the number of electrodes and keeping the size within reasonable limits. This is not merely a question of avoiding the difficulties of large electrode manufacture, but involves more efficient and satisfactory working of the furnace. It will readily be seen that distribution of temperature in the furnace is bound to be better as we multiply the relatively small areas where the heat is generated, and this is an important consideration. The objection that is raised to this proposal is the difficulty of regulating the rate of generation of energy at the various electrodes. It does not seem that this difficulty is a real one.

The roof problem is altogether a different one. It must be remembered that the heating effect in the steel furnace is generated in an arc and in a resistor formed by the slag, and that consequently the surface of the slag is intensely hot, particularly where the arc strikes it. These conditions are very severe, and combined with the corrosive action of the lime which is vaporized from the slag, make the roof renewals a heavy item in the cost of electric steel.

This problem has recently been the subject of careful study in two research laboratories, with one of which the writer is connected. As a result of a great deal of experimental work a brick made of silicon carbide has been manufactured, which it is believed will have a much longer life in the steel furnace than the silica brick now used. The brick is made by taking powdered or granular silicon carbide, mixing it with a suitable temporary binder, such as a solution of dextrine, molding and then heating in an electric furnace to the temperature at which silicon carbide is formed. Bricks made in this way have been used in the roof of an experimental steel furnace in one of these laboratories and then put to the severest test possible. The bottom of the furnace was purposely raised well above the normal level so as to bring the surface of the slag as close to the roof as possible, the actual distance in some experiments being only 10 in. (25.4 cm.) Then the furnace was worked at double the normal rate of generation of energy so that the heating of the roof was very intense, so much so that an ordinary silica roof would melt down rapidly and be completely destroyed in a single heat. Even under these very severe conditions the silicon carbide roof stood up perfectly. Experiments have also been made in other steel furnaces and these results confirmed. The most serious objection to a roof of this kind is its relatively great cost, but if it lasts a sufficiently long time it is nevertheless economical.

Twenty-five years ago Ferranti in England and Colby in this country worked on the very interesting furnaces known as the induction type. In this the secondary of a transformer consists of the metal to be melted. As in the case of the Siemens furnace the original inventors were too far ahead of the times and it was not till 10 or more years later that any commercial application of the furnaces was made. Since then the induction furnace has developed considerably and is now used with success in the manufacture of steel. An objection to the induction type is that its first cost is very great and certain problems connected with it become very serious when it is desired to build furnaces of large capacity. The worst of these is the very low power factor of the furnace. To overcome this objection it is necessary with large furnaces to have a generator furnishing currents of excessively low frequency. Thus, at the Võlklingen steel works a generator giving a current of 15 cycles is used, and for larger furnaces it has been proposed to use a five-cycle current. In an experimental induction furnace plant built by the writer's laboratories for an electric furnace company at Niagara Falls, the low power factor was corrected by using a synchronous motor as a condenser.

Nearly thirty years ago the Cowles brothers were working with the electric furnace in attempts to heat the charge of zinc retorts by electrical means. The principle involved in this case was mixing with the ore to be reduced a certain amount of carbon which not only acted as a reducing agent, but made the charge as a whole a conductor of the current. This furnace may be considered the forerunner of an immense number of electric furnaces in operation today, furnaces for making calcium carbide, the ferro alloys, iron ore smelting, graphitizing, etc. The Cowles furnace was a small one, but since its day the development of the electric furnace, helped by the corresponding development of electrical apparatus, has led to the construction of units of continually increasing size. To follow up the development of these furnaces would certainly transgress the limits of this paper, and instead, the development of a somewhat different type will be considered, because the writer has been more intimately associated with it, and because it contains points which are, perhaps, of more particular interest to the electrical engineer.

In Acheson's first experiments which led him to the discovery of silicon carbide (carborundum) he used a furnace of the Cowles type. It consisted of a small brick box with carbon terminals at each end so arranged that they could be moved in and out in a horizontal direction. This box was then filled with the mixture of sand and coke (clay and coke in the earlier experiments) and the terminals brought together, or very close to each other, and then gradually withdrawn as the furnace heated. It was soon observed that a more satisfactory way of constructing the furnace was to have stationary terminals connected to each other by means of a resistor composed of granular carbon and then surround this with the charge. With such an arrangement it was necessary to have some means by which the voltage could be regulated so as to keep the rate of generation of energy in the resistor constant throughout the run. This was found by Acheson to be a much more satisfactory way of working the silicon carbide furnace, and by experiment he found the best dimensions for his resistor. In the original small plant, where the furnaces had a capacity of about 100 kilowatts, the generator supplied current to a great bank of small transformers so that variations in the voltage could be obtained by suitable connections of the secondaries. When, however, a plant was established at Niagara Falls using furnaces of 750 kilowatts the problem of varying the voltage at the furnace terminals became important. This was solved by the construction of a large induction regulator to be used in the secondary circuit of the transformer which stepped down the primary current of 2200 volts to 160 volts. The induction regulator then made it possible to vary the e.m.f. by 60 volts on either side of this, so that at the furnace terminals the total range was from 100 to 220 volts. For furnaces of this resistance type the induction regulator is an ideal apparatus, and it is to be regretted that it is not more generally used. The objection raised to it is usually its relatively high cost, but the convenience and simplicity of the apparatus far more than compensate for the extra cost. In working with a furnace having a carbon resistor the resistance when starting is high and, consequently, to save time it is necessary to start the furnace with a high voltage. When the resistor becomes hot its resistance progressively decreases and the voltage must then be decreased to keep the rate of generation of energy constant. If this is done in a series of steps the results are not satisfactory, for when the maximum kilowatts are reached and the voltage is lowered one step the kilowatts are decreased proportionally, and in large furnaces it is a long time before the resistance drops to the point where the desired rate of generation of energy is again reached. This is a most inefficient method of working and the consequent loss will more than pay the interest on the cost of suitable apparatus for regulating the voltage.

Even at the time when these much larger furnaces were built the theoretical conditions involved in their construction were not understood, nor indeed for long afterwards. Thus, when the Niagara furnaces were first built the dimensions of the resistors were found to be altogether wrong, and about that time, when the writer took charge of the furnace department, experiments were tried with flat resistors, though an appreciation of the theoretical conditions of the problem shows at once that, other things equal, the resistor of circular cross-section must be best.

In any furnace in which the charge surrounds a resistor heated by means of an electric current it is obvious that the important consideration is the rate of generation of energy per unit surface of the resistor. The surrounding charge, or whatever it is desired to treat, can at a definite temperature absorb heat at a definite rate. Therefore, if it is desired to preserve the charge at a definite temperature it is necessary to generate the heat only so fast as the charge will absorb it. In other words, it is necessary that the watts should be a certain definite amount per unit surface of the resistor. The knowledge of the absolute value of the temperatures in such furnaces as those used in making silicon carbide is very scant, although some excellent work is now being done on this subject; but from the data obtained experimentally and the theoretical considerations of the working of such furnaces, it is possible to calculate relative temperatures with considerable accuracy.

This was well illustrated in the experimental work done by the writer in the difficult problem of making what Acheson called " siloxicon." This substance is formed by the reduction or partial reduction of silica and is combined in some way with carbon.

The great difficulty in making the material is due to the fact that at a temperature very slightly above that at which the reduction of silica by carbon begins the process goes too far and the well-known crystalline silicon carbide is formed. In order to calculate the dimensions of a resistor suitable for making the material the only data available were those which could be obtained from a study of conditions in the silicon carbide furnace. Without going into details it is sufficient to say that working in this way a furnace was soon designed which made large quantities of " siloxicon " without the formation of any serious quantity of crystalline silicon carbide.

The object in devoting so much consideration to this subject is because it illustrates in a marked manner the comparative ease with which electric furnaces can be adjusted to delicate temperature conditions. This is, of course, well known as regards small laboratory furnaces, but what we are considering now is a furnace about 30 ft.(9 m.) long, 12 ft. (3.6 m.) wide and 6 ft. (1.8 m.) high, having a capacity for a charge of about 60 tons.

The greatest progress in the electric furnace since Siemens's time has been in the arc furnaces of the kinds he used; in the induction furnaces of Ferranti and Colby; and in the resistance furnace of the Cowles type; but so far as the furnace depending on the use of a heating resistor, other than the charge, is concerned there has not been any great advance as regards apparatus of large capacity. The explanation of this is found in the structural difficulties involved. It is believed, however, that those can be overcome, and, moreover, that it is well worth while spending considerable effort in this direction. In the laboratories with which the writer is connected much time has been devoted to a study of this type of furnace, and more or less successful furnaces worked out. This kind of furnace for example lends itself very readily to a form of apparatus which is bound to be developed sooner or later where the heating is accomplished by means of fuel as well as the electric current. This has been done with success in furnaces on a large scale where the preliminary heating is carried on by means of fuel until a temperature is reached where it becomes economical to use the electric current to get the higher temperatures desired. Moreover, in such furnaces we may usefully employ nearly all of the electric current, by jacketing with burning gases, which eliminates nearly all radiation from the interior of the furnace by supplying the inevitable heat losses from fuel rather than electricity.

The question of the loss of heat through the walls of electric furnaces is a matter that is now attracting a great deal of attention, for its importance is very great. The writer has recently had occasion to give this matter careful consideration owing to the inefficient working of an electric furnace designed for some special smelting work. The testing of this furnace showed that the heat losses amounted to 50 per cent, but merely covering 25 per cent of the outer surface of the furnace with a moderately good heat insulator reduced this loss nearly 20 per cent.

Before closing the remarks on this type of furnace it may be of interest to note some experiments recently carried out with an electric kiln at the writer's laboratories. The kiln is the invention of Mr. John L. Harper and is of the continuous channel type. Two long channels run parallel to each other and through each of these passes a train of trucks in opposite directions. The center part of the kiln is heated electrically. With this arrangement, the trucks with their contents passing from the high-temperature part of the kiln, give up their heat to the trucks going to the high temperature part. Theoretically with an arrangement of this sort all that is required of the electric energy is to supply the heat losses from the kiln. Various experimental furnaces of this kind have been built, the chief object in view being a study of the structural features of the kiln, such as the best form of resistor, refractory linings, etc., also tests of the control of temperature, maximum temperature available, control of atmosphere, heat insulation, etc. The kiln was used for various purposes, but the principal experiments were made on porcelain with the production of " biscuit " and glazed ware. The control of temperature was found to be very good and the kiln was extremely simple to work, requiring very little attention.

It is not pretended that in this paper the subject of the development of the electric furnace has been more than superficially treated, the attempt being simply to take a few examples which would illustrate how the electric furnace has developed and indicate some of the problems involved in its construction and working today. This, naturally, confined the subject to a certain extent to matters within the writer's own experience; but it is hoped that this may prove somewhat more interesting than a mere catalogue of modern furnaces compiled from the literature on the subject.

DISCUSSION ON "THIRTY YEARS' PROGRESS IN THE ELECTRIC FURNACE" (FITZGERALD), BOSTON, MASS., JUNE 25, 1912.

Carl Hering: I am very glad to see that Mr. FitzGerald emphasized the fact that the cost of the energy is not the principal item in an electric furnace; so many people seem to think that it is; the cost of the electrodes, the cost of the furnace, the saving of labor, the better quality of the product, etc., should also be considered. If the product is more valuable you could stand a greater cost, and if the electric furnace should save labor, a very little labor cost will pay for much energy. Mr. FitzGerald speaks of using fuel heat in conjunction with electric heat. It seems to me it is better to use them in series than in multiple, to use electrical terms, that is, not to use them simultaneously, but to preheat with fuel and then get the higher temperatures by electric heat; the heat absorbed by preheating the metal will be found to be quite a large part of the total. Connecting carbon electrodes together, to avoid butts, gets over some of the electrode trouble, but on the other hand that junction is liable to break, allowing the butts to drop on to the bath, and to get those butts out of the bath is sometimes a very serious matter.

Alfred H. Cowles: Mr. FitzGerald has mentioned the Siemens furnace as a forerunner. I think we might as well go back to Sir Humphrey Davy's work in 1807 and 1808 as the forerunner. In 1885 the Siemens patent and work was encountered by my brother and myself in looking up the literature on electric furnaces. We found that Sir William Siemens had at the Paris Exposition in 1879 melted some iron in crucibles with an arc, but provided no method of confining the heat. His brother, Dr. Werner Siemens, has stated that Sir William Siemens never thought of the idea of reducing metals in his electric arc furnace. He had no bath or flux on top of the molten metal which might furnish resistance for the current to pass through, and therefore I think that his work cannot be considered in any manner an anticipation of the splendid work done by Heroult in evolving a resistance material in the form of a flux on top of his bath of molten iron. Mr. FitzGerald in referring to the work of my brother and myself spoke of it as a small work that we had done. In 1885 we ordered the largest of dynamos, in amperes, ever made up to that date, and after that we ordered the largest dynamo, in watts, ever specially designed for the purpose of operating electric furnaces. In 1886 we again ordered the largest dynamo (500 e.h.p.) ever designed up to that year, and after that ordered three more, the largest 700 h.p. All this work was done before a stroke of work was done at Niagara or by Acheson at Monongahela City. The production of calcium carbide, and of carborundum, although the latter's name was not then given to it, was accomplished in our work and a sample was left from 1887 until about 1898 in the Massachusetts Institute of Technology Museum, and in litigation that followed, that sample was produced and the

U. S. Court of Appeals in Philadelphia[1] decided that the Cowles brothers had not only made crystalline carbide of silicon four years ahead of Acheson, but had anticipated Acheson by one of our process patents. It took about six years to settle this litigation, and it is not entirely settled yet, after eighteen years have passed, as the damage case is now in the hands of the same court.

I dislike to speak in my own behalf, but when one meets a party of electricians in 1912, who are not familiar with what was going on in 1885 and '86, it seems necessary to say that between that time and this a great many of the facts have become twisted in the literature. In 1885 and '86 the literature was full of our work. In 1885 Dr. T. Sterry Hunt visited our works and asked us to repeat some tests for him. He stated to us that, from theories of his own, he believed the specific gravity of fused quartz should be 2 instead of 2½, that of crystalline quartz. The experiment made for him developed the specific gravity as about 2.15. He described this work on silicon and other reductions of the then rare elements by us in the Proceedings of the American Institute of Mining Engineers at the Montreal meeting, I think in 1886. We had melted and reduced SiO_2 before that time, and in the reduction retorts we found a suboxide of silicon. In the experiment that we made we found a yellow substance lying between the unreduced silica and the crystallized carbide of silicon. This was analyzed and found to be a suboxide of silicon and described by Professor Charles Mabery before the Franklin Institute in 1887, I think, and before other scientific bodies. It is now called siloxygen. The carbide of silicon that we made we mistook for DeVille's crystalline silicon. We also found amorphous masses which analysis showed to be silicon. In those experiments we obtained both the Si and SiC. While we did not analyze and discover the composition of carbide of silicon, we did produce it; and it was only during the litigation that we sent to the Massachusetts Institute of Technology and secured a sample of carbide of silicon that had been left there (after a lecture given by myself in February, 1886), and had it analyzed, and had its crystalline structure examined by Professor Robert H. Richards, the curator of the museum of the Massachusetts Institute of Technology. It was ascertained that we had formed the carbide of silicon about four years previous to Acheson's earliest work. The discovery that carborundum was a carbide of silicon was made by Mr. Muhlhauser, if I recall the name correctly, who about a year and a half after the first experiment with the furnace by Acheson in 1889, while in Acheson's employ, analyzed the substance and ascertained the true composition of it. I think that this gives the first record of this work on carborundum, which has not recently appeared in the public prints, but has appeared in the court discussions bearing on this subject.

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[1] Page 683, *Federal Reporter*, No 102.

W. B. Jackson: I would like to ask one question, and that is whether at the present time there is any likelihood of the electric furnace being constructed in such a manner and working in such a manner that it may become a valuable operation in valley power. My idea was that such a furnace might be very properly adopted for the use of such power.

F. A. J. FitzGerald: In regard to Mr. Cowles's remark, when I spoke of the Cowles furnaces being small, I meant that while they had furnaces having a capacity of perhaps 750 kw., then, they are small compared to some of those used today. They were the largest furnaces used at the time, far and away greater than those used in Europe or anywhere else; I meant small only in comparison with some of the 6000-kw. furnaces in use at the present time.

In regard to the question of valley power, we are working on that question now. For certain purposes you cannot use discontinuous furnaces. But there are certain conditions under which the electric furnace would be extremely useful for short runs of 8 hours.

I have been asked to explain how I would water-cool these electrodes if they were threaded and spliced. The water-cooled head is a ring that grasps the electrodes. The electrodes are threaded so that they may be screwed together and are slipped down through the ring as they wear away.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

SIMPLIFICATION OF ELECTROTHERMAL CALCULATIONS; THE WATT AND THERMAL OHM

BY CARL HERING

Modern tendencies are toward greater efficiency, in machinery as also in a more scientific management and in many other directions involving the saving of useless labor or wasted efforts, as exemplified, for instance, in simplified spelling, the use of abbreviations, the Esperanto language, etc. Obsolete, old-fashioned and inefficient machinery is willingly discarded for that which is more efficient; obsolete methods of management are discarded for better ones; economy in the physical labor of man is carefully studied and practised; yet in the very process which every engineer himself uses and which is more personal to him than any other, namely, the process of doing his mental work, the average engineer completely ignores the adoption of more efficient methods even when they are within his reach. In our numerous daily calculations we still adhere with astonishing tenacity to our antiquated, cumbersome, irrational, time-robbing, inherited systems of measures, although we have within reach systems which are far more efficient in the economy of mental energy.

We have before us an excellent example in the so-called absolute or c.g.s. system of units, which is so invaluable to the physicist. In this there is always one, and ***only one***, well-defined unit for every physical quantity, and practically all the conversion factors fall out of the calculations, as they are unity, because all the units are connected with each other by a unity relation.

We could readily have the benefits of such an ideally simple and time-saving system in our daily calculations by merely using as our practical units some fixed decimal multiples of these generally inconveniently small or large c.g.s. units. Our wise forefathers gave us some of these benefits when they established our present simple and very satisfactory system of practical electric units in which all relations are unity, and we should be everlastingly thankful to them for their forethought and wisdom.

But realizing the great mental inertia which has barred us in this country from the benefits of a great step in this direction in the form of the metric system, the introduction at the present time of such a more complete and radical change for the better as mentioned above, would seem hopeless. The chief reason is that each individual considers only his own small special field of work; there are too few broad-minded men who can see the matter in the light of the benefit to the community as a whole, and who can forget their own temporary inconvenience.

Although there exists this strong opposition to improving the efficiency of our mental work by changing existing units into more rational ones, there is an opportunity at least to take a step in this direction whenever an occasion arises to create a new unit where none has existed before. In fact in such a case it is, in the writer's opinion, a moral duty to our descendants to make such new units decimal multiples of the c.g.s. units, as those who established our electrical units did.

Such an occasion has arisen lately in connection with the flow of heat through bodies, a branch of applied science to which more attention has been given recently and will undoubtedly be given to a much greater extent in the near future; it has its application in the economy of thermal processes. Heat cannot be confined like electricity by practically perfect insulators; it will flow more or less through all bodies, hence will escape and be lost, thereby decreasing the efficiency of a thermal process. It therefore becomes important to be able to measure, calculate and predetermine such flows, and to do this requires that units be established for quantitatively expressing the physical quantities involved. The very rapid introduction of electric heating is making this important, particularly as its commercial success is dependent so largely, if not almost entirely, on the greater ability to prevent a waste of the energy, the prime cost of which is generally greater than that of combustion heat.

There is some property of heat which causes it to flow, another which offers resistance to such a flow, and as this resistance is different in different materials there is a thermal resistivity of materials; there is therefore also a conductance and conductivity;

the quantity of heat must be measurable, as also the current or flow of heat. To express, measure and calculate these quantities intelligently and conveniently, there should be a unit for each.

The purpose of the present article is to point out what the most rational values of these different units are and to urge their general adoption.

The selection of new units should, in the writer's opinion, be governed by two principles; one is to bring the new unit into the group based on the c.g.s. units by making it some decimal multiple of the corresponding unit in that system; and the other is to choose these decimal multiples so that in the most frequently occurring calculations the relations between the different units are unity, just as in our existing system of electrical units, and in the c.g.s. system.

The cause of a flow of heat is a difference of temperature. As there is unfortunately no unit of temperature in the c.g.s. system, we are compelled to adopt one of the thermometer scales and there is presumably no question that among these the centigrade system should be preferred. Hence the unit of difference of temperature which should be used in the present new group of units is the centigrade degree.

For expressing the flow of heat it would at first seem natural to use as a unit a transmission of one of the customary units of heat per second, like calories per second. It would then, however, not be in that preferred group of rationally interconnected units to which the c.g.s. and the electrical units belong, as there is no heat unit in that system. Heat is only one of the various forms of energy and one of the basic principles of a rational, interconnected system of units, is to have only one unit for each physical quantity no matter what form it is in. The c.g.s. unit of energy is the erg, hence this includes heat as well as all other forms of energy. It is therefore not correct to call a calorie per second a c.g.s. unit, as is not uncommonly done by able writers.

A flow or current of heat is physically a rate of transmission of energy, hence the only rational unit for measuring it in the c.g.s. system is the erg per second. The physicist would use this unit in his analytical deductions. This is more rational also because in many of our processes energy is transformed, sometimes repeatedly, from one form to another, and as it is the same energy it is not rational or mentally economical to keep changing the units in our calculations each time this same energy merely changes its form; the physicist would certainly not do so in an analytical discussion, and as his method is far simpler why should not the engineer also avail himself of this privilege?—it is directly within his reach.

According to the above principles, therefore, the practical unit of a flow or transmission of energy, be it in the form of heat or in any other form, should be a decimal multiple of the erg per second. As such a practical unit of a very suitable order of magnitude already exists in practise in the watt, it would be irrational to create a new one. Hence in the simplified system here recommended, the watt is chosen as the rational unit for the flow of heat. It is equal to 10,000,000 ergs per second.

When it is said that a heat flow of say 10 watts is passing through a thermal conductor, or is flowing out of its end or from a surface, it means that the amount of heat flowing is equal to that which would be generated continuously in an electrical conductor, lamp or coil in which 10 watts of electrical energy are being converted into heat. No conversion factors are then required, although the energy has changed from the electrical to the thermal form.

Some persons argue that in this as also in the adoption of the kilowatt in place of the horse power, we electrical engineers want others to adopt our electrical units to the exclusion of the older units, and they ask why we should not change ours to suit the older ones. This is manifestly unjust; what we ask is not that the other units be "electrified," but merely that these scattered, arbitrary, incommensurate and often quite irrational units should be changed so as to bring them into that rational c.g.s. group in which (nearly) all conversion factors disappear, and to which the electrical units already belong; and whenever the magnitude of the practical electrical unit for that quantity is of a convenient order, it certainly simplifies matters to adopt this already existing unit, like the watt in this case, instead of creating another one.

Having selected the centigrade degree as the unit of the cause of thermal flows, or what might popularly be called the thermal pressure, and having chosen the watt as the unit of the flow, then the rational unit of the resistance which opposes such a flow is that resistance which will allow one watt of heat current to flow through it when the difference in temperature at the ends is one centigrade degree. This means that these three units bear a unity relation to one another, just as, in accordance with Ohm's law, the unit ohm was so chosen that one volt will cause one ampere to flow through it.

This unit, which was recommended by the writer over a year ago, therefore is analogous to the ohm and the calculations involving it are like those for electrical resistances. The thermal resistance of a centimeter or inch cube is the specific resistance or resistivity, and the total resistance is equal to this resistivity multiplied by the ratio of the length to the section.

The flow of heat through a body in watts (assuming it to be perfectly insulated on the lateral surfaces) will be numerically equal to the difference of temperature at its ends, in centigrade degrees, divided by the thermal resistance of the body, provided the unit of resistance just defined is used. That is, if W represents the flow in watts, T the drop of temperature in centigrade degrees and R the thermal resistance in terms of this unit, then $W = T/R$, which on account of its identity with Ohm's law might be termed the thermal Ohm's law, especially as it is believed that Dr. Ohm discovered his famous electrical law through the analogy of the flow of electricity with the flow of heat, the laws of the latter having been determined earlier.

Owing to the analogy between the unit of thermal resistance, as thus defined, and the electric ohm, and in deference to Dr. Ohm, who about a century ago first pointed out the analogies between the two laws, it is suggested to call this unit of thermal resistance the *thermal ohm.*

When a unit is often used, it facilitates and simplifies matters to give it some distinctive name. It is, for instance, very convenient to be able to use the simple name " ampere " for the unit of an electric current, instead of its more cumbersome though quite correct equivalent the " volts per ohm." Or to use the name " ohm " in place of " volts per ampere." It seems almost essential to name two of such an interconnected group of three units—then why not name the third one also? Such a distinctive name is also useful to distinguish a unit more readily from other units of the same physical quantity when several are in use, as for instance in the case of feet, meters and inches, or pounds and kilograms, or horsepowers and kilowatts, etc.

Some persons, however, do not agree with the present writer in the advisability of thus naming this new unit, although they agree that the magnitude of the unit is the best; they prefer to define it each time it is used by stating that a thermal resistance when given in terms of this unit is equal to so-and-so many " degrees per watt," on the same principle that the name of the ohm is unnecessary, as this unit could correctly be specified as the number of " volts per ampere." Unfortunately neither of these two phrases carries with it the often very useful conception that the physical quantity referred to is a resistance. The writer thinks it better to give it a characteristic name and therefore advocates the term " thermal ohm " as a simple one which carries with it an explanation that it represents a thermal resistance, while the last word " ohm " indicates that it belongs to the same ideal group of units to which the electric ohm belongs, in which the values are always some decimal multiples of the c.g.s. units.

Whenever the difference of temperature between the ends of a thermal conductor, stated in centigrade degrees, is divided by the thermal flow in watts, the quotient, being the degrees per watt, is the thermal resistance in thermal ohms.

Dr. A. E. Kennelly first suggested this name, but the present writer had believed that it was for a unit of a different magnitude than the one here proposed. After the present paper was written, the writer found that the unit to which it had been applied was also the same (see A. I. E. E. TRANSACTIONS, 1907, Vol. XXVI, II, p. 974, a paper which the writer had not previously seen); Dr. Kennelly, however, seemed to use it there in a general sense for any thermal resistance unit, for on p. 993 of that paper he applies the reciprocal to " thermal-mhos-per-cm. in *gram-calorie* measure;" moreover the whole matter was only incidental in that paper.

That this unit is of a convenient size for use in practical work is shown in various tables of values of the thermal resistivities of various materials[1] and surfaces[2] which were gathered from various sources and reduced by the writer to thermal ohms. The metals, for instance, have thermal resistivities of about one-quarter to three thermal ohms for one centimeter cube; solid refractory materials like brick, about 40 to 200; loose granular or fibrous materials about 300 to 4000. Surfaces from which heat is emitted seem to have a surface resistance of several thousand to less than one thermal ohm per square inch, depending upon the nature of the surface and the temperatures.

In thermal problems, as in electrical ones, it is often convenient and time saving, in the calculations occurring in practise,

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1. " Flow of Heat through Bodies." *Metallurg. & Chem. Engineering*, Dec. 1911, p. 652.

2. " Flow of Heat through Contact Surfaces." *Metallurg. & Chem. Engineering*, Jan. 1912, p. 40.

to use the thermal resistances of bodies as resistances and not carry the calculation each time to the extent of determining the loss of heat through it, as was formerly done before thermal resistances came into more general use. This would apply, for instance, where such resistances are used as thermal insulators. This often saves many unnecessary calculations, and it also eliminates the temperature from such calculations, except in so far as the temperature coefficient of the thermal resistivity is concerned. A wall of a furnace or the thermal insulation of a cooking device can be specified simply as having a resistance of so-and-so-many thermal ohms.

Although in most engineering problems of an electrothermic nature, like those applying to stoves and furnaces, it is far simpler to use resistances instead of conductances, as is also generally true in purely electric problems, yet it may sometimes be desirable to use thermal conductances and conductivities, and for this purpose the units for the latter should of course be the true reciprocals of the resistance and resistivity units. For consistency the name " thermal mho " is recommended for the corresponding unit of thermal conductance.

A more detailed discussion of this unit of thermal resistance was published by the writer over a year ago[3], in which article a complete set of the conversion factors was given for reducing values in other units to those in the units here suggested, and the reverse, as also numerical examples illustrating the use of this unit in practise. These conversion factors are as follows:

TABLE OF CONVERSION FACTORS

(NOTE.—A flow or radiation of heat may be measured in watts, in gram-calories per second, or in ergs per second. In this table the term " c.g.s. unit," that is, the absolute unit, refers to the true ones based on the erg per second; those often called " c.g.s. units" and based on the gram-calorie are here given under the latter term. The centigrade degree is understood to be meant in all these units.)

Thermal Resistance.

Thermal ohms:
=centigrade degrees ÷ watts = degrees per watt.
= 1 ÷ thermal mhos.

1 thermal ohm:
= a resistance requiring 1° C. per watt of flow.
= 4.18617 gram-calorie units; approx. 50/12.
= 0.0000001 c.g.s. unit of thermal resistance.

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[3] " Thermal Resistance and Conductance; the Thermal Ohm and Thermal Mho." *Metallurg. & Chem. Engineering*, Jan. 1911, p. 13.

1 gram-calorie unit:
= a resistance requiring 1° C. per flow of a gram-calorie per second.
= 0.238882 thermal ohm; approx. 24/100.
= 2.38882×10^{-8} c.g.s. units of thermal resistance.

1 c.g.s. unit of thermal resistance:
= a resistance requiring 1° C. per flow of an erg per second.
= 10,000,000. thermal ohms.
= 41,861,700. gram-calorie units.

Thermal Conductance.

Thermal mhos:
= watts ÷ centigrade degrees = watts per degree.
= 1 ÷ thermal ohms.

1 thermal mho:
= a conductance permitting a flow of 1 watt per degree.
= 0.238882 gram-calorie unit; approx. 24/100.
= 10,000,000. c.g.s. units of thermal conductance.

1 gram-calorie unit:
= a conductance permitting a flow of 1 gram-calorie per second per degree.
= 4.18617 thermal mhos; approx. 50/12.
= 41,861,700. c.g.s. units of thermal conductance.

1 c.g.s. unit of thermal conductance:
= a conductance permitting a flow of 1 erg per second per degree.
= 0.0000001 thermal mho.
= 2.38882×10^{-8} gram-calorie units.

Thermal Resistivities.

NOTE.—These are the reciprocals of the corresponding conductivity units.

1 gram-calorie, centimeter cube unit:
= 0.393700 gram-calorie, inch cube unit; appprox. 4/10.
= 0.238882 thermal ohm, centimeter cube unit; approx 24/100.
= 0.0940478 thermal ohm, inch cube unit; approx. 2/21.
= 2.38882×10^{-8}c.g.s. units of resistivity.

1 gram-calorie, inch cube unit:
= 2.54001 gram-calorie, centimeter cube units; approx. 10/4.
= 0.606762 thermal ohm, centimeter cube unit; approx. 3/5.
= 0.238882 thermal ohm, inch cube unit; approx. 24/100.
= 6.06762×10^{-8} c.g.s. units of resistivity.

1 thermal ohm, centimeter cube unit:
= 4.18617 gram-calorie, centimeter cube units; approx. 50/12.
= 1.64809 gram-calorie, inch cube units; approx. 5/3.
= 0.393700 thermal ohm, inch cube units; approx. 4/10.
= 10^{-7} c.g.s. unit of resistivity.

1 thermal ohm, inch cube unit:
= 10.6329 gram-calorie, centimeter cube units; approx. 21/2.
= 4.18617 gram-calorie, inch cube units; approx. 50/12.
= 2.54001 thermal ohm, centimeter cube units; approx. 10/4.
= 2.54001×10^{-7} c.g.s. units of resistivity.

1 c.g.s. unit of resistivity:
= 4.18617×10^7 gram-calorie, centimeter cube, units.
= 1.64809×10^7 gram-calorie, inch cube units.
= 10^7 thermal ohm, centimeter cube units.
= 3.93700×10^6 thermal ohm, inch cube units.

Thermal Conductivities.

NOTE.—These are the reciprocals of the corresponding resistivity units.

1 c.g.s. unit of conductivity:
= 2.54001×10^{-7} thermal mho, inch cube unit.
= 10^{-7} thermal mho, centimeter cube unit.
= 6.06762×10^{-8} gram-calorie, inch cube unit.
= 2.38882×10^{-8} gram-calorie, centimeter cube unit.

1 thermal mho, inch cube unit:
= 3.93700×10^6 c.g.s. units of conductivity.
= 0.393700 thermal mho, centimeter cube unit; approx. 4/10.
= 0.238882 gram-calorie, inch cube unit; approx. 24/100.
= 0.0940478 gram-calorie, centimeter cube unit; approx. 2/21.

1 thermal mho, centimeter cube unit:
= 10^7 c.g.s. units of conductivity.
= 2.54001 thermal mho, inch cube units; approx. 10/4.
= 0.606762 gram-calorie, inch cube unit; approx. 3/5.
= 0.238882 gram-calorie, centimeter cube unit; approx. 24/100.

1 gram-calorie, inch cube unit:
= 1.64809×10^7 c.g.s. units of conductivity.
= 4.18617 thermal mho, inch cube units; approx. 50/12.
= 1.64809 thermal mho, centimeter cube units; approx. 5/3.
= 0.393700 gram-calorie, centimeter cube unit; approx. 4/10.

1 gram-calorie centimeter cube unit:
= 4.18617×10^7 c.g.s. units of conductivity.
= 10.6329 thermal mho, inch cube units; approx. 21/2.
= 4.18617 thermal mho, centimeter cube units; approx. 50/12.
= 2.54001 gram-calories, inch cube units; approx. 10/4.

As the calculations involving thermal resistances and flows of heat through them become so simple when these units are used, and are identical with the analagous electrical ones, it seems superfluous to give any numerical examples here as illustrations. Such examples are given in some of the papers that have been referred to. Attention, however, is here called to the fact that although the temperature coefficients of thermal resistivities are probably of about the same general order of magnitude as those of electric conductivities and therefore not large per degree, yet the ranges of temperature are sometimes so great, as in furnaces for instance, that these changes should be taken into consideration

Besides using watts and thermal ohms to simplify thermal calculations, it will greatly simplify numerous other calculations in electrothermic work to apply the same reasoning to the heat unit itself, that is, to abandon all the several so-called heat units, namely the two calories, the British thermal unit, and the hybrid pound-centigrade unit, and use the watt-hour instead. This brings the heat unit into the c.g.s. group and relieves all subsequent calculations of the troublesome conversion factors involving the mechanical or electrical equivalents of heat; such conversion factors then become unity.

This is readily done by converting the values of the physical constants of materials given in calories or B.t.u., in the tables, once for all into watt-hours; the numerous electrothermal engineering calculations based on them then become extremely simple, so simple in fact that many of them can be done mentally.

This would mean converting all such thermal constants as specific heats, latent heats, and heats of chemical combinations, once for all into watt-hours, thereby avoiding the incessant repetition of the reductions involving incommensurate conversion factors in all the numerous subsequent calculations. It would then be stated, for instance, that the energy necessary to heat, melt and raise the temperature of a pound of steel to a certain number of degrees is so-and-so-many kilowatt-hours per pound. This is discussed in another paper by the writer.[5]

The conversion factors are as follows: One kilogram-calorie equals 1.1628 or approximately 7/6 watt-hours; one thermal unit (pound-Fahrenheit unit or B.t.u.) equals 0.29303 or approximately 5/17 watt-hours; one watt-hour equals 0.85998 or approximately 6/7 kilogram-calories and 3.4127 or approximately 17/5 thermal units.

It may at first seem somewhat inconsistent to use the watt-hour instead of the joule for the equivalent of the heat unit in this simplified system. But although the joule is theoretically the more rational unit, yet electric energy in practise is now universally expressed and measured in watt-hours or kilowatt-hours and never in joules, hence by using the former the trouble-

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[4] "Effects of the Variations of Thermal Resistivities with the Temperature." *Trans. Amer. Electrochem. Society*, Vol. XXI, 1912, p. 511.

[5] "Uniformity and Simplicity in Electrochemical and Electrothermal Calculations." *Trans. Amer. Electrochem. Soc.*, Vol. XXI, 1912, p. 499.

some factor of 3600 (the number of seconds in an hour) is eliminated by becoming unity.

The simplifications in calculations, by thus working within the same group as the c.g.s. units, is so great that it may often reduce the mental labor, even in thermal problems which do not involve electrical energy; one would then reduce the original data at the start to this group of units, and the final results back again, which would enable one to make all the calculations involving the design and proportioning (and these are often by far the more numerous) in the simple system, just as in some classes of work it is simpler to convert the original data into the metric system, then make all the tests and numerous engineering calculations in that system, and convert the final results back into the original units.

DISCUSSION ON "SIMPLIFICATION OF ELECTROTHERMAL CALCULATIONS; THE WATT AND THERMAL OHM" (HERING), BOSTON, MASS., JUNE 25, 1912.

H. B. Gale: I think the new unit proposed in this paper is a very practicable and useful one, and I hope it will become adopted as one of the new tools of the profession. I have spent a great deal of my time in the last few years in making calculations on electric heating, and have found it necessary to work out a table of constants for calculating watts transmitted by different substances per degree difference of temperature, and I am very much obliged to Dr. Hering for giving me a name for the constants of my table.

Carl Hering: Dr. Kennelly suggested the name for that unit.

H. B. Gale: I am grateful for the name anyway. But it does seem to me that the name thermal ohm is open to objection, because it is liable to be confused with the electric ohm. These will be abbreviated ultimately, and it occurred to me that it could be called a " thermohm," and then it would not be confused with the other. Or you could reduce it to " therm." I believe that the unit is one that is destined to be exceedingly useful and to simplify our work very greatly.

Alfred H. Cowles: It seems to me that the adoption of such a unit would lead us around a great circular path, with the ultimate discovery that we do not come back to the beginning point. We start with old work done about a century ago, from which there was defined the dyne of force, the electrostatic units, and the centigrade degree of temperature. Later, we passed to electrodynamics, with the evolution of its derived set of units dependent for their magnitude upon those units that had formerly been determined and the velocity of light, barring the cutting down of the electromagnetic unit of rate of flow ten-fold in order to secure a more convenient unit of rate of flow, the ampere.

In the study of heat, the units have been developed independently, all upon the c.g.s. system with the exception of the unit (T) for the rise in temperature or difference in temperature potential. This latter is arbitrary. The watt as a measure of rate of energy flow per second, per second, is directly derived and dependent upon the magnitudes of the volt and ampere. If we use it to express a rate of flow of energy, in the form of heat conducted per second, per second, it would seem to me that we would have to have also a thermic volt to go with the proposed thermic ohm, and there should be some natural relation between the thermic volt and the electric volt, and also some natural relation between the thermic ohm and the electric ohm, but this would imply something to correspond in its nature to the ampere. But the watt is a product of a volt times an ampere, while an ampere is a unit by itself expressing a rate of flow of one coulomb per second per second.

Here, in the failure of a watt and an ampere to correspond in their natures, we find that in our circular path we have not returned to the point of beginning. The electric ohm is that resistance which will permit one ampere to flow with a fall of potential of one volt between two terminals. We may note that the absolute nature of this resistance or its mechanics is not clear to one's mental conception, but R multiplied by amperes squared times seconds gives units of energy, watts or joules. If we evolve a law of heat conduction that is analogous to Ohm's law of electric conduction, it seems apparent, nevertheless, that we cannot use the watt as a rate of energy flow if we are to introduce a thermic volt, and also a thermic ohm.

We can, however, call one degree centigrade a thermic volt, which gives us a thermic ohm arbitrary in its nature, very much as the degree centigrade is, for it would depend upon the latter. Maintaining the watt as it must be, a constant, we can change the magnitude of the thermic volt to any amount, with a corresponding change occurring in the magnitude of the thermic ohm. For instance, were we to make the thermic volt 96,000 deg. cent. to correspond numerically to the electrochemical equivalent in electrolysis, and call it unity, then one watt equals one thermic volt having as its equivalent 96,000 deg. cent. of temperature. Now making the intangible thermic ohm 96,000 times larger in magnitude, as proposed by Dr. Hering, we would have two natural relationships between electricity and heat introduced into the proposed formula, thus making 96,000 a unity—it would be a thermic volt. We already have the watt per second, per second, as a rate of flow of energy, and recurring to Ohm's law in its new form, we have one watt of energy will flow per second when a difference of potential of one thermic unit exists between two sides of a wall whose ends, top and bottom and sides are perfectly insulated, having a resistance of one thermic ohm. In this form the numerical relations between a new thermic ohm and the electric ohm may be made to mean something valuable. A natural numerical relation between the volt unit as a measure of difference of electric potential and the temperature, centigrade degree, unit as a measure of difference of heat potential, can then be derived.

Carl Hering: I think if Mr. Cowles will examine these relations more carefully he will find that he is mistaken in some of his remarks. In the flow of heat the unit he calls "thermic volt" already exists in the degree of temperature. When the flow of heat is expressed in watts, it has its analogy in an electric circuit in the form of a flow in amperes. Instead of this leading to complications it seems to me to lead to simplification.

Alfred H. Cowles: I am pleased to hear that stated, for, in a paper read before the Electrochemical Society at the first Niagara Falls meeting, I pointed out the very fact that differences of heat potential in a body were perfectly analogous to differences of electric potential, and if one could introduce a unit analogous to the ampere, one could study the heat flow in the same manner as flow of electricity is now studied.

I think " watt " as used by Mr. Hering expresses a quantity of energy rather than a rate of flow or flux of energy. A new name should be supplied bearing the same relation to a watt that an ampere bears to a coulomb. In the latter portion of my remarks I described a thermic volt whose magnitude is a multiple of the degree centigrade. This discloses a means of establishing those units, without making the thermic ohm dependent for its magnitude on the arbitrary value of the degree centigrade, amd maintaining them within the c.g.s. system.

Carl Hering: Mr. Gale's acknowledgment of the usefulness of the thermal ohm agrees with statements made to me by others who have had to make calculations of heat flows. The fact that those who have used this unit find it useful, is the best kind of an endorsement.

The names " thermohm " and " therm " which he suggests may perhaps be considered better by some, as also the term " thom." But in the writer's opinion too much abbreviation sometimes involves a loss of time rather than a gain; this is apt to be the case when the longer name is self-explanatory and the shorter one requires a definition which one must look up. The writer favors self-explanatory names.

Concerning Mr. Cowles's remarks, I think he will find some of his criticisms answered in the paper itself. The generally used heat units are not based on the c. g. s. system, as he supposes; the unit of heat in the c. g. s. system is the erg, while in the independent system it is the calorie. He is mistaken in saying that the watt is " the rate of energy flow per second, per second;" the watt is a unit of power which is energy per second, and therefore is a true measure of a flow of energy, or in general, of a transmission of energy from one place to another. Nor is a rate of flow of energy " heat conducted per second, per second." There seems to be no " natural relation " between what he calls the thermic volt and the electric volt, nor between the thermal ohm and the electric ohm; they are merely analogous; they are totally different physical quantities, hence there can be no equivalent between them any more than there could be between a meter and a kilogram; the two latter are connected by the fact that a cubic decimeter of water weighs a kilogram, and it might be possible that some such connection might be found between the thermal and their analogous electric units.

An ampere is not "one coulomb per second, per second," but simply a " coulomb per second." There is no reason why the watt and ampere should " correspond in their natures;" they are simply analogous when the watt is used in its broader sense of a power unit. We ought to dismiss from our minds the idea that the watt is an electrical unit, which it is not; it is the decimal multiple of the c.g.s. unit of power and therefore measures power in any form, whether electrical, thermal, mechanical, chemical, luminous, acoustical, etc. Mr. Cowles uses watts and joules indiscriminately as " units of energy;" this is incorrect, joules are measures of energy and watts are measures of power, that is, rate of energy. He is also wrong in stating that resistance " multiplied by amperes squared, times seconds," gives watts; it gives joules. A " watt per second, per second," is not " a rate of flow of energy." Many unfortunate errors have arisen in this confusion between power and energy, and it is often found today in the expression " cost of a kilowatt," when a kilowatt-hour or kilowatt-year is meant; a cost of power is meaningless unless the time in which it is used is also given.

As I have already said, I think Mr. Cowles's suggestion of a " thermic volt " equal to 96,000 centigrade degrees would lead to complication rather than to simplification, and it would increase our already too numerous conversion factors; the writer has urged a reduction of these time-robbing numbers rather than increasing them.

Mr. Cowles is mistaken when he thinks that the watt, as used by me in the paper, expresses " a quantity of energy;" it does not, it expresses a time rate of energy. The watt, as used for a flow of heat, already bears the same relation to the corresponding unit of heat in this same system (namely the joule), as the ampere bears to the coulomb, hence his suggestion to supply a new name is not necessary.

I cannot endorse Mr. Cowles's suggestions and I have no reason to change my belief that great simplification would result in our calculations if we made all our units decimal multiples of the c.g.s. units, as the electrical units are, and that we should tend to go in that direction whenever there is an opportunity presented such as the introduction of a new unit where none has existed before, as was the case with the thermal ohm.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

VACUA

BY W. R. WHITNEY

The purpose of this article is to publish a few observations made in the research laboratory on some phenomena in vacua, as they may possibly be of interest to others who are working in the field of evacuated apparatus.

The subject has a double interest because at first glance it seems difficult to see how there can be much ground for study, or material and phenomena for useful investigation, in such an apparently confined volume of nothingness as the vacuum of an incandescent lamp. The many actual developments from this lack of material are interesting, and there is the added interest due to the fact that there are to be found in these lamps examples of many of the phenomena of gaseous ions which are receiving so much study in our day.

It has long been known that the life of an incandescent lamp is greatly influenced by the quality of its vacuum. In general, one may say that the better the vacuum, at least up to a certain point and until recently, the longer the life of the lamp. In the early days of lamp making, many schemes were devised to improve the vacua. This was then all the more necessary, as the mechanical methods of lamp-exhausting were very much inferior to present ones. The harmful effects of oxygen and water vapor, both of which reacted upon the filaments, were well known and many ways were devised for removing them.

What seems to be an especially interesting method of supplementing the vacuum pumps was the method of Malignani. This process, in its most perfect form, consisted in distilling into the bulb a small amount of some such substance as arsenic, sulphur, iodine, or phosphorus. At the instant when one of these vapors was introduced, he passed a high current through the filament, the lamp being closed from the pump. This has long been the common commercial process for lamps which are to operate on voltages above 50, and many millions of lamps have been exhausted by its aid.

In case of incandescent lamps where the voltage is above 50 for a fair brilliancy of filament, a blue discharge passes through the bulb and this blue quickly disappears when such vapors are introduced. The blue discharge seemed to be necessary for any considerable improvement of the vacuum, due to such vapors as phosphorus, and this led to the assumption that the gases still left in the lamp by the pump were removed quickly during the blue glow and probably by the vapors which were at the same time being deposited on the glass. Although the facts were pretty well known, we performed experiments to study the phenomena. It was found that when the vacuum was measured by a McLeod gage, the sudden marked improvement of vacuum was easily proven. For example, in experiments carried on by Mr. Willey, of the laboratory, when the pump had produced a vacuum of 0.030 mm. mercury and the cock leading to it was closed, a trace of phosphorus was distilled into the bulb while the filament was very hot and a blue glow had appeared; then about as quickly as the gage could be read the pressure had fallen to 0.002 or 0.001 mm.

That this improvement of vacuum is quite commonly produced when vapors of any kind are caused to condense in the space is not new. It even takes place markedly when the filament is first heated to very high temperature without added vapor, and a *blue glow* also passes through the lamp at the time. In improving the vacuum this latter way, however, it is known that the filament is injured and apparently a part of its material has been vaporized. This process soon causes blackening of the bulb by carbon.

This vaporization of phosphorus into the lamp at the moment when the pump has done its work, has long been the commercial method of finishing the exhaustion of incandescent lamps. The fact that even the carbon alone tended to the same end, though at the expense of the filament, being recognized, it became of interest to get a clearer view of this phenomenon.

In other words, if an incandescent lamp was burned while connected to a McLeod gage and the vacuum became poorer, the changes of vacuum might be measured by the gage from time to time. If, on the other hand, the vacuum improved so that the pressure tended to become less than the vapor pressure of mercury at the temperature of the gage, then the gage would not only not measure it, but the mercury vapor might even have affected the life of the lamp. When experiments were made to determine the effect of the vapor of mercury at the low pressures corresponding to a micron, which is the vapor pressure of mercury at 15 deg. cent., very peculiar results were obtained and the lamps showed very early blackening. It looked as though even the presence of this constant mercury pressure was fatal to the lamp. Therefore the discovery of a more practical vacuum gage was desirable.

Without committing ourselves to a theory, we can describe one or two interesting experiments with mercury vapor. It was first discovered that an incandescent lamp grew black very quickly when attached to a mercury column which served as a gage to indicate evolution of gas. No such combination could be made to last over a few hours. The lamp blackened just as though it was in an imperfect vacuum. It is hard to see how the mercury can have any chemical effect upon the filament as oxygen or water have, and the effect is common to carbon and tungsten lamps. Many lamps were then made which were exhausted as perfect lamps are exhausted, except that a small quantity of mercury was left in the bulb. It was assumed that this would not interfere with the removal of air and moisture and might even assist by the washing effect of the mercury vapor, mechanically removing air. Lamps were also made in which a large quantity of mercury was placed, the lamp put into an oven above the boiling point of mercury and the air washed out by the distilling mercury, no pump being used. When the mercury was nearly all removed the bulb was sealed. This method, if no visible mercury is left in the bulb, is capable of giving good lamps, but where a visible drop of mercury was present the lamp would show a persistent blue glow and rapidly blacken, even below its normal voltage. In some cases it would arc between the leads, exactly as in the case of poorly exhausted lamps.

Lamps were also made to which were attached tubes which carried small globules of mercury. When these side tubes were short and straight, such as one or two inches, and the lamp was exhausted as well as possible on the pump, the blackening of the bulb started at once when the entire glass was at ordinary temperature. If the side tube with its mercury was then submerged in different cooling mixtures, the length of time for a given blackening was increased. For example, at room temperature the lamp would be blackened so as to correspond to 80 per cent of its original candlepower, in a few minutes. When the side tube containing the mercury was at 0 deg. cent. this time became two or three hours; and when cooled in a freezing mixture at 20 deg. cent. the life to 80 per cent was over 75 hours. Such differences were also noted when the pressure of mercury vapor was controlled by using different cadmium amalgams, the amalgams higher in mercury corresponding to the shorter lamp life.

It was interesting to note also that by lengthening the side tube containing the mercury, the rate of this deposition of filament material in the bulb was decreased.

In a set of experiments at ordinary temperatures the length of the side tube was increased and it was wound as a spiral. This reduced the rate at which the mercury could reach the bulb proper. In this case, instead of there being a continuous faint blue glow, as there is when the mercury is in a short side tube, the blue glow appeared and disappeared continuously and regularly. It looked as though there was a certain pressure of the vapor necessary before the blue discharge could occur and that when this was reached, the sudden discharge produced the blue and cleared the vacuum to a much lower pressure. Then mercury vapor distilled anew from the long side tube until again the necessary pressure was reached, when the process of clean-up repeated itself.

If the lamp bulb was kept very hot, the blackening was reduced and even done away with altogether, as though the deposition of the mercury vapor upon the glass by the discharge signalized by the blue glow, could not take place. If, however, water vapor was present, even in very small amount, the blackening would take place very rapidly, even in the absence of mercury. In other words, most ordinarily exhausted lamps will blacken relatively quickly if allowed to burn in a heated oven. In general, the hotter the oven the more rapid the blackening, but this process is largely, if not entirely, due toi mperfect exhaustion. All glass contains water which can be removed but slowly, even at relatively high temperatures. It has even been found that indefinite heating of a lamp connected to the vacuum pump is not capable of removal of all of this water. If exhaustion be carried on for a very long time at room temperature, then merely raising the temperature will cause liberation of more gas, and after heating and exhausting to an equilibrium condition at say 200 deg.cent. more water will be produced on heating to 300 deg. cent. and still more at 400 deg. For this reason it is customary to exhaust at as high a temperature as possible. At 400 deg. cent. the ordinary glass has reached its limit, owing to the proximity of the softening point. For this reason we have had to exhaust the oven in which the lamps were being exhausted, and thus remove the atmospheric pressure, in order to study the water evolution at higher temperatures.

For a long time it was impossible to follow the change of vacuum in a lamp, because the pressure could very evidently not be reduced below the vapor pressure of the mercury of the McLeod gage attached to the lamp. It has long been known, also, that the current passed through the space of the bulb to a considerable extent, and that this varied with the degree of vacuum, etc. A very complete discussion and description of experiments on this so-called Edison effect are given by Professor Fleming, in Vol. 42 of the *Philosophical Magazine*. In general, the conclusions are that in the vacuum of an incandescent lamp a current can flow across the space from the negative and of the filament to any conductor in the bulb, if this be so located that particles passing in straight line from the negative leg may come into contact with this conductor. This latter was usually a small platinum plate, and to it, as anode, a continuous current flowed from the negative half, or end of the filament, except when it was intermittently shielded from direct emanations. The current, often of several milliamperes, was measured by a galvanometer connected between the metal plate and the positive terminal of the lamp. It is known that the materials of the filaments distill in straight lines and cast well-defined shadows, because the mean free path at this pressure is greater than the diameter of the bulb, and it was natural to assume that this vaporizing carbon carried electric charges of negative sign. This assumption might seem to require the more rapid wasting away of the negative half of the filament than the positive, but no data are present to prove this. When condenser charges were superposed on this apparatus it was found that with the negative end connected with the negative side of the condenser, the condenser was at once discharged. When connected oppositely, it was not discharged. Current could pass as negative from the hot conductor or filament, but not from the cold plate, nor could positive current pass from either the hot or cold terminal.

In connection with this work of Fleming's, we have studied the effect of the condition of vacuum on the current, and also found that the presence of gas is necessary for this negative discharge. In general, the higher the pressure of the gas, when this does not exceed a few thousandths of a millimeter of mercury, the greater is the current. This makes it seem improbable that the current is solely dependent on the passage of carbon or tungsten from the filament to the positive electrode, though it leaves the possibility open that the current may be carried by gaseous ions produced by negatively charged material coming from the negatively charged filament.

By using alternating current and a metal electrode in a carbon lamp, Fleming obtained direct current on the circuit connecting the metal plate to either terminal of the lamp and the current was in the direction expected, the plate being negative to the terminal.

This outfit is thus obviously a rectifier, and it has been so used by Fleming for low currents.

The effect of a magnetic field on this gaseous conduction, just as in the case of metallic bismuth, is to increase the resistance.

It was finally found that the Crookes radiometer was a very sensitive gage for the changes of pressure in lamps, and by its use the changes could be followed in a qualitative manner, even throughout the life of the lamp, by having the radiometer sealed directly to the lamp. Dewar has shown the sensitiveness of this apparatus in the *Proc. Roy. Soc.*, 1907, 531.

The radiometer consists of a glass bulb containing a perpendicular needle with a glass cap on which are four aluminum arms with a mica vane at the end of each. One face of each mica vane is coated with lamp-black. When the radiometer is evacuated to a high degree, the effect of radiant energy or light is to cause rotation, which is believed to be due to the fact that the molecules of gas take up energy from the blackened surface of the vanes more than from the plain surfaces, the black absorbing more of the incident energy and thus locally heating the gas molecules. These in the rarefied atmosphere largely give off this energy to the walls of the apparatus by direct impact, rather than to other molecules in the neighborhood of the vane. This results in a motion of the vane opposite to the motion of the gas molecules, because the unblackened face of the vane receives impact mostly from these cooler molecules.

The vacuum of the lamp as sealed from the pump approximates a few microns and is poor enough so that the radiometer rotates rapidly when exposed to light. By using a fairly constant light intensity and noting its effect upon a radiometer attached to a lamp which was lighted for intervals, it was seen that the radiometer gradually rotated more and more slowly, and finally after a period of normal lamp brilliancy of from 12 to 36 hours on tungsten lamps, it would stop rotating altogether. At this point it was found that a more sensitive measure of still higher vacua could be gained by starting in the dark by mechanical motion a rotation of the vanes of a definite speed, and noting the rate of speed decay on standing. This was done by proper spinning of the whole apparatus in the hand and then getting the rate of decrease in this rotation of the vanes by counting definite revolutions after definite time intervals. Here the friction of the residual gases was merely overcoming the momentum imparted mechanically to the vanes at start. In this way, even by comparing the minutes required for the radiometer to come to a stop, quite interesting information was obtained.

This method was not developed into a quantitative one, though it might have been. The radiometer method shows us, however, some interesting facts which are worth describing. Using the common type of radiometer often seen in jewelers' windows and sealing this directly to a lamp made for 110-volt circuit, the radiometer would rotate when in daylight. This showed the presence of some gas in the lamp, and the McLeod gage used at the time of sealing the lamp from the pump showed approximately 2 microns. If, now, the radiometer and the lamp were removed to a dark room and a rotating motion imparted to the vanes, they would proceed to rotate for about a minute, this time depending somewhat on the particular radiometer used, as well as on the condition of the vacuum.

Since at the moment when the filament was at bright heat and the vacuum very poor (so poor, in fact, that if the pressure were maintained constant the lamp would blacken in a few minutes), the vacuum greatly improved, due to some action occurring together with spattering of the filament, it seemed important to know more about the phenomena. We assume that the gas at first present goes to the walls of the lamp and is held there, possibly absorbed by the small quantity of deposited filament material. It is always possible to drive the greater part of it back into the vacuum space by warming the glass. It seemed perfectly possible that the process might be a cyclic one; that is, the gas carrying to the walls of the bulb some of the filament material and not of necessity remaining there, but possibly returning for a fresh supply. This continued process might account for the limited life of an incandescent lamp. It did not seem necessary to assume that there was any measurable rate of simple distillation from a carbon filament at the temperature of operation, though such a phenomenon could account for limited life of filament. It even seemed possible that the cyclic process, instead of being physical, might well be expressed as a chemical one, such as we know could exist, and might continue between the oxides of carbon and carbon itself. At the high temperature of the filament, carbon monoxid would be expected, but this, at a lower temperature, would form CO_2 and free carbon, the latter being deposited upon the glass. The free CO_2 coming into contact with the hot carbon filament would again form carbon monoxid, and thus the process be repeated continuously until the filament was burned through or the lamp became too black to be of use. It was therefore desirable to get a closer insight into the phenomena in the lamp at a pressure of a few microns.

Similar considerations can apply equally well to the case of tungsten filament lamps. In the case of osmium lamps this reasoning, extended, explains the fact that the presence of a little oxygen in the lamp was necessary to prevent blackening of the bulb by the deposited metal. A little oxygen in a carbon lamp might similarly remove deposited carbon from the glass and deposit it upon the filament, if the temperature at the two points were suitable, but with this element it seems impracticable because the oxid formed is not easily reduced below the CO state, thus differing from osmium.

While the lamp to which a radiometer was attached was not lighted, practically no change in vacuum could be detected by the radiometer. Therefore there is no leak of air from without. If, however, the lamp was lighted, the reverse was true. On allowing the lamp to be lighted for a few seconds only, and then cooling and testing in the dark room as before, the duration of rotation would usually be shorter, thus indicating a liberation of gas into the bulb space by this short time of burning. If, however, the lamp were allowed to burn at a normal brilliancy for a longer time and the same vacuum test was made from time to time on the unlighted lamp in the dark room, it was found that the duration of the impressed rotation rapidly increased. In many cases a rotation lasting 15 minutes would be produced by allowing the lamp to burn 24 hours. This phenomenon of automatic vacuum improvement received the name of the "clean-up." While the clean-up, as measured in this rough way, did not seem to take place in all lamps to the same degree, it was always present under ordinary conditions.

Other types of vacuum lamps improved their vacua on running. In fact, no lamp, unless we except the mercury arc, fails to do so. The well-known Moore tubular system of lighting, which is a development of the Crookes tube, consumes the gas, and for that reason an automatic valve was invented which supplies air to the tube when the vacuum improves to a certain point. It is also an old story, in the case of the cathode and X-ray tubes. X-ray tubes are usually made with a salt, such as potassium chlorate or potassium hydrate, mica, asbestos, etc., in an attached side tube. This may be heated when the tube in use attains too high degree of evacuation, and in this way gas is liberated into the bulb. This is in turn removed from the vacuous space by the operation of the tube. A natural question is raised at once: whât becomes of these disappearing gases? In some cases they are probably forced or shot into the glass itself, for some of these old glasses bubble on being heated to the softening point. Possibly the greater part of the gas is absorbed by the exceedingly finely divided metal, which slowly deposits on the glass as it vaporizes from the electrode.

If an incandescent lamp, the vacuum of which had been thus cleaned up, was allowed to stand unlighted at ordinary temperature, the vacuum, as indicated by the test, would gradually grow poorer, though it would seldom fall to the starting value. If the bulb were heated in an oven at 100 deg. cent. for a few moments, it would also show a poor vacuum again on cooling. If such a spoiled vacuum lamp was again lighted, it would at once commence to recover its previous high vacuum. There was no indication of a fatigue evinced in lamps thus treated.

This explains the fact noticed in the case of most factory-made incandescent lamps, that their life at constant voltage varies with the external temperature. It is as though the gas, which is at first present in the space of the sealed bulb and is then thrown upon the walls by the clean-up, is also continually driven off from the walls at a rate dependent upon the wall temperature, and the deposition is bound up with some loss of filament material.

The experiments with the radiometers naturally led to attempts to develop more nearly quantitative apparatus which would still measure the low pressures of gas under consideration in incandescent lamps. Among the promising methods was that described by Pirani (*Ber. Deut. Phys. Ges.* 1906, 686). This was further developed by Dr. Hale of this laboratory, as described in the *Transactions* of the American Electrochemical Society, 1911.

This gage depends on the principal that energy loss from a heated wire in the vacuum to be measured depends on the pressure of the gas present. When the temperature of this wire is low (100 deg. cent., for example) the losses by radiation are relatively small, so that the rate of total loss at a constant temperature of wire would serve to determine the gas pressure. Conversely the temperature of this wire, if supplied with constant energy, from the battery, for example, would be higher, the lower the gas pressure. This latter scheme was adopted by Dr. Hale, and the gage consisted of a glass bulb sealed directly to the lamp to be measured and contained about two feet of fine platinum wire. This was heated by a current of constant watts and the temperature of the wire was given by knowing its temperature resistance coefficient and measuring the actual resistance for the case in test.

The measurement involved extrapolation towards perfect vacua from comparative measurements made with the new gage and the McLeod gage at pressures high enough so that the latter is reliable. Hale concluded that he could measure differences of pressure of one hundred-thousandth of a millimeter of mercury, or a hundredth part of the vapor pressure of mercury at zero centigrade. Here was a gage which, unlike the McLeod, exerted no appreciable vapor pressure of its own and therefore could serve to indicate the existing pressure at any period of the life of the lamp. It could disclose the fact if gases were produced within the burning lamp, if the seals or glass leaked at all, and how the clean-up actually changed the vacuum as indicated by the radiometer experiments. In using this gage new and interesting phenomena were disclosed, which must be further studied. In certain cases vacua a little more than perfect are indicated by this gage, and this suggests possible dissociation of the very attenuated gas. Barring this fact, it seems as though the clean-up effect proceeds to as nearly perfect vacuum as we can measure even qualitatively.

DISCUSSION on "VACUA" (WHITNEY), BOSTON, MASS., JUNE 25, 1912.

A Member: Dr. Whitney refers to the gases which disappear from the incandescent lamp, and refers to the same phenomena in connection with the X-ray tube, and he calls attention to the fact that some of these old glasses from the old bulbs, either from the incandescent lamp or from the X-ray tube, bubble on being heated to the softening point. I hope that Dr. Whitney will clear up the claims of certain English physicists, and of German physicists, as to this matter. Dr. Robert Poole of the University of Berlin repeated some experiments made by an English physicist and he declares absolutely that the Englishman is mistaken; that an old glass does not give off this gas when it is under pressure in a vacuum so that the gas would be given off. Dr. Whitney refers to the fact that the glass when heated to a softening point will bubble, referring to the old glass, and I know a new glass does this as well, the conditions being that the old glass or new glass must be in a vacuum of something less than one millimeter actual pressure. I hope that Dr. Whitney will clear up this point, because the question of where the gas goes to is really a question that is important.

W. R. Whitney: I don't want to try to clear that up yet, because we don't know enough. There are various theories about it, but I cannot decide it.

Alfred H. Cowles: In a letter from A. H. Bucherer, of Bonn University, it is stated that in Europe they have a new method of creating a much higher vacuum than anything heretofore secured. I do not know whether that method is known in this country.

W. R. Whitney: As a further contribution to the question of gases within the glass of old X-ray tubes, lamps, etc., I will add that such gas also appears in the glass of old mercury rectifiers. Mr. Van Brunt, of the research laboratory, heated in a blast lamp the glass side-arms of old mercury rectifiers. The portions of the glass near the anodes turned white. On microscopic examination it was noted that this part of the glass was filled with minute bubbles which were not there prior to the heat treatment. They were within the glass itself, though much nearer the inner surface of the tube than the outer. This was shown by grinding and polishing in a plane which made a very acute angle with the surface of the glass. We did not consider the appearance of these gases in such glass an open question, but believe the question now is as to the source of the gas. Are these bubbles produced from gas which was dissolved or driven into the glass during the operation of the lamp or tube, or was the gas produced by a reaction between some injected material such as the electrode material and the material of the glass, or was it produced by the action of leakage current, static, etc., which caused a sort of electrolysis of the glass, the gaseous products remaining dissolved until the glass was subsequently heated?

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912

METALLIC TUNGSTEN AND SOME OF ITS APPLICATIONS

BY W. D. COOLIDGE

Tungsten does not occur as such in nature, but in the form of compounds it is pretty well distributed. The most important ores are sheelite or calcium tungstate and wolframite or iron-manganese tungstate. The principal source of the ore at this time in this country is Boulder County, Colorado.

From the ore it is a simple matter to get the yellow oxide (trioxide) of tungsten. And the trioxide may be reduced in various ways, as with hydrogen, zinc and carbon, to metallic tungsten. The product so obtained is in the shape of a powder ranging in color from gray to black, depending upon the fineness of its state of subdivision.

Owing to its very high melting point, it was for a long time impossible to get the pure powdered metal into the form of a dense coherent homogeneous mass. Two Austrians, Messrs. Just and Hanaman[1], working in Vienna, finally succeeded, however, in producing the pure metal in this condition and in filamentary form, and by using it as an incandescent filament became the inventors of the tungsten lamp.

One of their processes consisted in first mixing the finely divided tungsten powder with a carbonaceous binding agent. The plastic mass so obtained was then extruded through a small orifice. The resulting thread was heated in the absence of air, to carbonize the binder. The fragile body so produced consisted of tungsten powder and carbon and was electrically conducting. If it had been used in this condition it would have been

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[1] U. S. Patent No. 1,018,502.

worthless owing to the presence of carbon, which lowers the melting point and besides this, slowly distills out in a vacuum, causing a blackening of the lamp globe. But Just and Hanaman found that the carbon could be removed by heating the filament to a high temperature, by passing current through it, in an atmosphere of hydrogen and water vapor. This high temperature treatment not only removes carbon but also causes the filament, under the action of capillary forces, to shrink to a dense homogeneous body.

Various other processes were subsequently devised for making small filaments of pure tungsten. But these were all alike in this, that they started with the finely divided metal or oxide or some other compound of the metal. By the help of some agglomerant, the finely divided material was then worked into a plastic mass. This was then brought into filamentary form by extrusion through a die, and was then raised to a high temperature under such conditions that nothing but pure tungsten remained, the filament sintering under the application of the high temperature to a dense coherent body.

Filaments produced in this way showed the melting point of pure tungsten (about 3000 deg. cent.) And they were very satisfactory as lamp filaments except in one respect—they were weak mechanically. They were, like spun glass, highly elastic but absolutely brittle; that is, they could not, by cold bending, be given the slightest permanent deformation.

In the above-mentioned brittle condition, metallic tungsten had, as such, but one single commercial application, namely as a lamp filament. This application was, however, extremely important—so much so that a vast amount of the most painstaking investigation work was carried out both in this country and abroad in the endeavor to produce a ductile form of tungsten. Without some such enormous commercial interest at stake, it seems extremely doubtful whether the product sought for would ever have been produced. For no one knew but what metallic tungsten, like the silicon of today, was, at room temperature, inherently brittle. And the evidence in support of the theory that it was inherently brittle was almost overwhelming.

At a meeting of the Institute in May, 1910, the author presented a paper[2] telling of the successful reaching of the goal—the production of ductile tungsten. At that time samples of drawn wire were shown and the hope was expressed that within a short

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[2] TRANSACTIONS A.I.E.E., 1910, Vol. XXIX, Part II, pp. 961 to 965.

time laboratory processes could be brought to a point where the public could profit by the new invention. This development has taken place so rapidly that today the bulk of the world's supply of tungsten lamps is made from drawn wire.

As has been said above, so long as tungsten was a brittle metal it found but one single technical application. But with the advent of ductile tungsten, the whole situation is changed, and the metal has now, apart from its use as a lamp filament, assumed a very considerable degree of technical importance.

Before proceeding to a discussion of some of the new applications it may be well to summarize here some of the most important properties of wrought tungsten. Most of these data have already been published.[3]

Physical Properties. Wrought tungsten is a bright steel-colored metal having the same density as gold, 19.3. (This varies somewhat with the amount of mechanical working which the specimen has had.)

The strength and pliability both increase with the amount of mechanical working. The fracture may be very coarsely crystalline, or it may resemble that of a very fine grained tool steel or it may be fibrous and silky in appearance, or it may lie anywhere between these extremes, the appearance in each case depending upon the chemical purity and upon the preceding thermal and mechanical treatment. The tensile strengths measured have ranged from 460,000 lb. (208,652 kg.) per sq. in. (6.45 sq. cm.) for a wire 0.005 in. (0.127 mm.) in diameter to 610,000 lb. (276,691 kg.) for a 0.0012-in. (0.0305 mm.) wire.

Tungsten is hardened by working but not by heating and quenching. Similarly tungsten containing carbon is not appreciably affected by quenching. The hardness imparted by working may be entirely removed by carrying the metal to white heat.

The ductility is extreme, as is shown by the fact that wire only 0.0006 in. (0.0152 mm.) in diameter is now produced in large quantity.

Tungsten is non-magnetic.

The electrical resistivity at 25 deg. cent., expressed in microhms per centimeter cube, is 6.2 for the hard drawn wire and 5.0 for

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[3] C. G. Fink, *Transactions Am. Electrochem. Soc.*, Vol. 17, pp. 229 to 234 (1910).

W. E. Ruder, *Jour. Amer. Chem. Soc.*, April, 1912.

the same annealed. The corresponding data for annealed copper and annealed platinum are 1.87 and 11.1 respectively.

The temperature coefficient of electrical resistivity per degree between 0 deg. and 170 deg. cent. is 0.0051.

Assuming the Franz-Wiedemann law to hold for the relation of heat to electrical conductivity, we may calculate the heat conductivity of annealed wrought tungsten to be 0.37 times that of copper and 2.2 times that of platinum.

The coefficient of heat expansion per degree from 20 deg. to 100 deg. cent., is 336×10^{-8}, which is about 0.26 that of platinum.

Chemical Properties. Wrought tungsten does not tarnish upon standing in the air. Upon heating it to a temperature of three or four hundred degrees, however, it oxidizes superficially and turns blue just as steel does. At bright red heat the oxide volatilizes and the metal wastes away more or less rapidly, depending upon the temperature.

It is quite resistant to the action of most acids, being entirely unaffected at room temperature by either dilute or concentrated hydrofluoric, hydrochloric, nitric, and sulphuric acids. With aqua regia at room temperature the action is very slight. At a higher temperature, 110 deg. cent., there is no action in the case of hydrofluoric, concentrated nitric and dilute sulphuric acids, while the action is but slight in the case of dilute and concentrated hydrochloric, concentrated sulphuric, dilute nitric, and aqua regia. There is no action in the case of a mixture of sulphuric and chromic acids, but the metal dissolves rapidly in a mixture of hydrofluoric and nitric acids.

An aqueous solution of caustic potash has no effect on wrought tungsten, but the fused salt does attack the metal slowly.

In aqueous solutions of sodium or potassium carbonate or mixtures of the two, tungsten dissolves slowly, the action being considerably hastened by the addition of potassium nitrate.

ELECTRICAL CONTACTS OF WROUGHT TUNGSTEN

Under the conditions pertaining in many electrical make-and-break devices, as in magnetos, spark coils, voltage regulators, railway signal relays, telegraph and telephone relays, telegraph sending keys, etc., wrought tungsten has proved to be far superior to platinum or platinum-iridium for the contact points.

This was not in any sense an obvious application, for tungsten is not, like platinum, a metal difficult to oxidize. It might well have been assumed that under the heat of the minute arcs which form when the contacts are separated, the tungsten would oxidize at the points where arcing has taken place, and that non-conducting layers would thus be formed which would produce a high and variable contact resistance. In fact our first experiments bore out this theory. But subsequent work showed that the difficulty in these early experiments came from the fact that, at the time, we were unable to make a good thermal and electrical joint between the tungsten and the contact-carrying members. With the attainment of a good conducting joint, our results changed completely. The contacts no longer rose to the same high temperature and the oxidation decreased to little or nothing. Moreover, in case there was any oxidation, it was to the lower and electrically conducting oxides.

Tungsten contacts wear longer than those of platinum or platinum-iridium. This is doubtless due largely to the lower vapor pressure. At temperatures at which platinum volatilizes badly, tungsten has a very low vapor pressure. Besides this the heat conductivity of tungsten is more than twice that of platinum, and as a result, the contact faces do not rise to the same high temperature. (In comparison with platinum-iridium alloys, the ratio of heat conductivities is still more favorable to tungsten). In connection with the life of contacts, another important consideration is that of hardness. Tungsten is so hard that it does not batter down at all under the continual hammering which the contacts get in service.

Tungsten contacts show less tendency to stick than do contacts of platinum or platinum-iridium. This is to be attributed in part to the higher melting point of tungsten. There seems to be another factor here, however, for while we are able, by proper manipulation, securely to weld together two pieces of platinum at a temperature considerably below the melting point, it has not as yet been possible, except by actual fusion, to produce anything more than a very weak adhesion between two pieces of tungsten.

One minor and unexpected advantage connected with the use of tungsten contacts consists in the fact that they seem less sensitive to the accidental presence of oil than do platinum contacts.

Allusion has already been made to the difficulty at first experienced in producing satisfactory thermal contact between tungsten and the metal comprising the contact-carrying member.

This was due to the fact that tungsten cannot be satisfactorily soldered by any of the ordinary processes. This difficulty has been overcome in the following way: The little disk of tungsten, which is to serve as contact point, is attached by means of copper to the head of an iron tack. Copper does not alloy with tungsten, but, under suitable conditions, it wets it, and then adheres firmly. This gives a joint of high thermal and electrical conductivity between the tungsten and the head of the iron tack. The shank of the tack is then either pressed in, or brazed, or riveted to the contact-carrying member.

WROUGHT TUNGSTEN AS TARGET IN A RÖNTGEN (X-RAY) TUBE

This has proved to be, both from the scientific and practical points of view, an exceptionally interesting application.

Until recently platinum has been almost universally regarded as the best target material, and it has so long held undisputed sway in this field that the Röntgen ray worker has come to look upon its limitations as inherent in the Röntgen tube.

With the advent of dense, forged pieces of pure malleable tungsten, the possibilities of the Röntgen tube are greatly extended.

The desiderata in a material to be used as the anticathode or target are the following:

1. High specific gravity.
2. High melting point.
3. High heat conductivity.
4. Low vapor pressure at high temperature.

The reasons why the above qualities are desirable follow readily from a brief consideration of the theory of Röntgen-ray production.

From the concave cathode, electrically charged particles, the electrons, are shot out at high velocity in a direction normal to the surface. The paths of these particles converge and the target is placed at or near the point of strongest convergence, the focus point. When the electron meets an obstruction, as the target, its velocity is reduced, and the denser the target the more rapid is the retardation. The more rapid the retardation the greater is the amplitude of the electromagnetic pulse, the Röntgen-ray, sent out. Here, then, is a need for high specific gravity; that of forged tungsten is but little less than that of platinum.

In modern Röntgen-ray practise, powerful apparatus, running sometimes to a capacity of 10 and even 15 kilowatts, is used to excite the tube. A considerable part (perhaps as much as one-third) of the energy delivered to the tube is transformed into heat at the point where the cathode rays bombard the target. Where platinum is used it has been found necessary, to prevent melting, to place the target beyond the focus of the cathode so as to spread the bombardment over a larger area. As a radiograph is a shadow picture, and as the source of the Röntgen-ray is the bombarded area of the target, this enlarging of that area is clearly an undesirable thing to do, as the larger area will mean more overlapping and less definition in the resulting picture. In this way, the melting point of platinum has been the limiting feature of the Röntgen tube. The capacity of the tube has been increased by water-cooling the platinum or by using as a target a large mass of copper having a very thin platinum face. But the limit, although raised by these artifices, has still been the melting point of the platinum.

Tungsten has a much higher melting point (3000 deg. cent. as against 1755 deg. for platinum), and so, even with sharp focusing of the cathode rays on the target, permits the use of more energy than has hitherto been possible; for the high temperature to which it can run enables it to radiate more heat, and its better heat conductivity permits a more rapid flow of heat from the focus spot to the surrounding metal.

Stability of vacuum in a Röntgen tube is of the utmost importance, as the character of the rays is so largely determined by the vacuum. Metal, which, under the influence of the high temperature, vaporizes from the target, condenses on the glass in finely divided form and absorbs relatively large amounts of gas, thus changing the vacuum. At high temperatures tungsten vaporizes least of all the metals.

Two distinct types of tungsten target are being tried out experimentally in competition with one another.

The first of these consists of a heavy copper block with a disk of wrought tungsten attached to the face. This is similar to the platinum targets which have been in use for some years. The function of the copper is simply to conduct heat away from the tungsten and to act as a heat storage reservoir. In this latter capacity it is much more effective than would at first seem possible, owing to the fact that while the rate of energy input is high the time is correspondingly short, a single excitation of the tube lasting for perhaps only a half second. It is interesting to note that it would take an energy input of over 60 kilowatts acting for a second to raise the temperature of a half-pound mass of copper by 700 deg. cent.

The second type is for the first time made possible by the advent of wrought tungsten. In this type, the target consists entirely of refractory metal, and this is allowed to heat up to such temperatures that it is capable of radiating relatively large quantities of energy. Tungsten at its melting point is capable of radiating about 375 watts per sq. cm. This means that a tungsten disk 3 cm. in diameter and 0.2 cm. thick would, if its entire mass were at the melting point, be radiating energy at the rate of over 5 kilowatts. (The same cylinder, if made of platinum and run at 1750 deg., the melting point of platinum, would radiate only about one-twentieth as much). It would not of course be practicable to run the entire tungsten mass at the melting point, and, owing to the resistance to heat flow, the focal spot would of course come to the melting point while the periphery was at a considerably lower temperature. But such a target would at least be able to radiate, continuously, relatively large amounts of energy.

The target has, for a long time, been the most vulnerable point in the tube, but this is no longer true. For either of the above types of tungsten target can be made so good that failure of the tubes as they are now built will be due to other causes.

THE TUNGSTEN- OR MOLYBDENUM-WOUND ELECTRIC FURNACE

This has been fully described in an article by Winne and Dantsizen[4]. This is not only a useful adjunct to scientific investigation work, but has already become a very important factory tool. When wound upon a body of alundum, either of these metals makes possible the attainment of higher temperatures than can be obtained with a platinum-wound furnace. And as refractories of higher and higher melting points are produced the temperature range of this furnace will be extended.

TUNGSTEN PROJECTILES

The use of wrought tungsten as a projectile is being carefully investigated. It offers, in this field, possibilities not possessed by any other metal.

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[4] R. Winne & C. Dantsizen, *Transactions Am. Electrochem. Soc.* Vol. 20, pp. 287 to 290 (1911).

The present small arm service projectile is made of lead with a jacket of copper-nickel alloy. The principal advantage of lead over iron, which would of course be cheaper, is that it has a higher specific gravity. Because of this fact a lead bullet will have a smaller cross-section, and will therefore encounter less air resistance to its flight, than will an iron bullet of the same weight, and will therefore give a flatter trajectory and longer range. An iron bullet of the same diameter as the lead bullet could of course be given the same weight by increasing its length. But this would at once necessitate giving it a higher rotational velocity to keep its axis tangential to its flight. To impart this added rotational velocity calls for the expenditure of energy and so leaves less for velocity of translation. The lead bullet, then, with its higher density makes possible a flatter trajectory and longer range. With the exception of tungsten, lead is the densest metal which can be considered for this purpose, for gold is the cheapest of the other elements having a higher specific gravity than lead. The density of wrought tungsten is 19.3 while that of lead is 11.5.

For military purposes, the softness of lead is not an advantage, a soft-nosed bullet being tabooed in civilized warfare. For this reason and because of the fact that it is too weak to hold the rifling, it has to be jacketed with the copper-nickel alloy. To take the rifling and to act as a gas check, the tungsten bullet will require a copper band or its equivalent at the base.

The hardness and high tensile strength of wrought tungsten will give high penetrating power.

The high melting point of tungsten will prevent it from being harmfully upset at the base by the combined action of the high temperature and rapid impact due to the combustion of the powder charge. (An unsymmetrical upsetting of the base of a projectile is very prejudicial to accuracy).

It would be a very simple matter to calculate the constants of the trajectory of a tungsten projectile were it not for the fact that the high density removes it too far from the present base line. For such calculations one quantity is lacking, the so-called "form factor." This factor could itself be calculated if it contained, as the name would seem to imply, only the dimensions and the specific gravity, but there are also involved in it all of the errors due to simplifying assumptions which have been made in connection with the mathematical derivation of formulas. It therefore becomes necessary to determine experimentally the constants of the trajectory of tungsten bullets, and this work is now being carried out.

Chemical Ware of Tungsten

Because of its inertness to many chemical agents, wrought tungsten in the form of dishes is certain to find many industrial applications. Small dishes have already been made successfully, and work is already under way looking to the production of larger sizes.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 25, 1912.

THE CONVECTION AND CONDUCTION OF HEAT IN GASES

BY IRVING LANGMUIR

In a previous paper[1] the author has shown that the "convection" of heat from hot wires in a gas consists essentially of *conduction* through a film of relatively stationary gas around the wire. From this theory the following method was derived for calculating the power necessary to maintain a wire at any given temperature.

The loss of energy from a wire is made up of two parts, radiation and convection. Let us call this convection **W**, expressed in watts per cm. of length of the wire. Then **W** is equal to the product of two factors, thus

$$\mathbf{W} = \mathbf{s}\,(\varphi_2 - \varphi_1) \tag{1}$$

The first factor, **s**, is called the "shape factor" and depends only on the ratio of the diameter of the wire, *a*, to the diameter, *b*, of the conducting film around the wire. This relation is

$$\mathbf{s} = \frac{2\pi}{ln\,\frac{b}{a}} \tag{2}$$

But **s** can be calculated directly, without a knowledge of the film diameter *b*, by solving the following equation:

$$\frac{a}{B} = \frac{\mathbf{s}}{\pi}\,\epsilon^{-\frac{2\pi}{\mathbf{s}}} \tag{3}$$

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1. *Physical Review*, Vol. 34, p. 401, (1912).

Here a is the diameter of the wire and B is the thickness of the conducting film for the case of convection from a plane surface.

The second factor in (1) is $\varphi_2 - \varphi_1$ where φ depends only on the heat conductivity of the air, **k**, (in watts per cm.) and the temperature of the wire and of the atmosphere. Thus

$$\varphi_1 = \int_0^{T_1} \mathbf{k}\, dT \qquad \varphi_2 = \int_0^{T_2} \mathbf{k}\, dT \tag{4}$$

Here T_1 is the temperature of the atmosphere and T_2 the temperature of the wire.

Both of the operations involved in (3) and (4) are made very easy by plotting two curves, one giving the relation of **s** to $\frac{a}{B}$ and the other relation of φ to T. Data for the plotting of these curves are given in the paper referred to above.

Thus the only data necessary for a calculation of the free convection from a horizontal wire (of given diameter and temperature) in a gas of known temperature, are

1. The heat conductivity of the gas as a function of the temperature.
2. The value of B.

It was shown experimentally that for air at room temperature and atmospheric pressure, B is equal to 0.43 cm. and is independent of the temperature, T_2, of the wire, even when this varies from slightly above room temperature up to the melting point of platinum.

It was shown that with five different sizes of wire ranging from $a = 0.0038$ cm. up to $a = 0.0500$ cm., the energy **W** calculated from (1) and (3) agreed excellently with experiments. This is equivalent to saying that the experimentally determined values of B were found to be independent of the diameter of the wire used in the experiment.

The theory would indicate that B should vary with

1. The nature of the gas.
2. The pressure of the gas.
3. The temperature of the gas.
4. In the case of forced convection, B should vary with the wind velocity.

The present paper will deal with the effect of the second and fourth of the above factors on the thickness of the conducting film.

Kennelly in his excellent paper on *The Convection of Heat from Small Copper Wires*[2] has investigated the effect of the following factors:

1. Diameter of wire. Varied from 0.011 to 0.069 cm.
2. Temperature of wire. With the free convection tests this varied from 40 deg. cent. to 200 deg. cent., but with the forced convection temperatures as high as 325 deg. cent. were used.
3. Pressure of air. Varied from 12 up to 190 cm. of mercury.
4. Wind velocity. Varied from 0 up to 2000 cm. per second.

He did not investigate other gases than air, nor try air at other than room temperature.

Kennelly derives certain purely empirical formulas to express his results. Combining them, he gives for **W**, the watts lost by free convection per cm. of length,

$$\mathbf{W} = (0.0004 + 0.0064a)\,(T_2 - T_1)P^{0.9\sqrt[3]{a}} \tag{5}$$

where a is the diameter of the wire and P is the pressure of air in atmospheres.

For forced convection he finds

$$\mathbf{W} = (0.00003 + 0.00580a)\,(T_2 - T_1)\,\sqrt{v + 25} \tag{6}$$

where v is the wind velocity in cm. per sec.

Thus to express his results on free convection he needs to use four empirical constants and to express the results on forced convection three more are needed. But even with all these empirical constants, the calculated values do not agree very well with the experiments. The average difference between the calculated and observed values of **W** for experiments on free convection is approximately 12 per cent, while in one experiment the differences are as high as 30 per cent.

Let us now analyze Kennelly's data more closely and apply to then the theory of the conducting film, thus deriving the relation between the film thickness B and the pressure and wind velocity of the air.

KENNELLY'S DATA ON FREE CONVECTION

The experimental results on free convection are given by Kennelly in ten logarithmic plots, the coordinates being

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[2] TRANSACTIONS A. I. E. E., 1909, Vol. XXVIII, I, p. 363.

pressures and current through the wire. He does not give the resistances of the wires at the temperature of the experiment, but does give the resistance of each of the wires at 0 deg. cent. and gives the elevation of temperature above room temperature, calculated from the resistance. He used for this calculation the formula .

$$R_T = R_0 (1 + 0.0042\ T_c)$$

where R_T is the resistance at the temperature T_c (in deg. cent.) and R_0 is the resistance at 0 deg. cent. He did not measure the temperature coefficient of the wire used, but assumed that the wires were of pure copper and that the temperature coefficient was that given above. He does not state the room temperature during the experiments, so I have assumed it to be 20 deg. cent., and have thus calculated the resistance of the wires from his data on the temperature elevation above room temperature and from the given temperature coefficient. By taking the product of the resistance per cm. and the square of the current, I have then calculated **W**, the watts per cm. supplied to the wire. This is given in the following tables as " **W** obs. "

Kennelly is very uncertain as to how large the correction for radiation should be, and finally assumes that the copper wires radiate 94 per cent as much as a black body at the same temperature. This correction amounts to about 2 per cent for the smallest wire and becomes about 8 per cent of the total energy for the largest wire. But there are ample data in the literature to show that radiation from a bright metallic surface is very much less than 94 per cent of that from a black body. A great deal of recent work has shown conclusively that the reflectivity, **r**, of any metal for heat rays of wave length longer than $\lambda = 6\ \mu$ is accurately given by Hagen and Ruben's formula[3]

$$1 - \mathbf{r} = 0.365 \sqrt{\frac{\sigma}{\lambda}}$$

where σ = specific electrical resistance of the metal

λ = wave length of the light.

By Wien's displacement law the wave length λ_M of the light of greatest intensity in the spectrum from a black body at temperature T is

$$\lambda_M = \frac{0.29}{T} \text{ cm.}$$

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[3] *Ann. Phys.*, 8. 1, 1902.

Therefore for radiation of heat at room temperature, about 300 deg. K.[4], the wave length would be about 0.0009 cm. or 9μ.

Now for copper $\sigma = 1.7 \times 10^{-6}$
and for platinum $\sigma = 11.0 \times 10^{-6}$
Whence approximately
for copper $1 - r = 0.0158$
and for platinum $1 - r = 0.040$.

That is, at room temperature copper would radiate 1.6 per cent and platinum about 4.0 per cent as much as a black body. This result for platinum is in fairly good agreement with Lummer and Kurlbaum's[5] measurements on the radiation from platinum. In any case, it is a very safe conclusion that the radiation from bright copper surfaces is much less than 50 per cent and therefore that it would have been better if Kennelly had neglected radiation, instead of correcting for it.

Therefore, in using Kennelly's data, we shall use the total watts as observed, rather than the values he gives for convection. At the relatively low temperatures at which his experiments were carried on, radiation probably does not exceed one per cent of the total losses.

In Table I the first column gives the diameter of the wire in cm. The second column gives the temperature elevation above room temperature given by Kennelly and calculated by him from the resistance. In the second column there is also given $\varphi_2 - \varphi_1$, taken from a very large scale curve prepared from the data given in the previous paper. T_1 is assumed to be 293 deg. K. The third column gives the resistance per cm. of length of the wire, calculated from the resistance at 0 deg. cent. given by Kennelly and from the temperature coefficient 0.0042 used by him in calculating $T_2 - T_1$. Hence any error in assuming a wrong value for this temperature coefficient is eliminated.

In the fourth and fifth columns are the data obtained directly from the plots given by Kennelly. Smooth curves were drawn through the points given by Kennelly without any reference to the straight lines that he uses to express his results. The ordinates of these curves at three or four well-distributed pressures were read off and are given in column V. The pressures are given in megabars (*i.e.*, 0.987 atmospheric pressure). In column VI are given the watts per cm. obtained simply by multiplying the figures in column III by the square of the

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[4] Degrees Kelvin (absolute temperature).

[5] *Verh. Phys. Ges.*, Berlin, 17, 106, 1898.

TABLE I

KENNELLY'S EXPERIMENTS ON FREE CONVECTION

I	II	III	IV	V	VI	VII	VIII	IX	X
Diam. of wire cm.	T_2-T_1 and $\phi_1-\phi_2$	Resistance $\frac{\text{ohms}}{\text{cm.}}$	Pressure P megabars	Amps.	W obs.	W calc.	B obs. cm.	B_1 calc. cm.	n
0.0114	165.0	0.0273	0.325	1.72	0.0810	0.0811	1.04	0.46	−0.73
			1.00	1.89	0.0978	0.0980	0.44		
			1.70	1.98	0.1072	0.1017	0.31		
	0.0497		2.25	2.02	0.1114	0.1142	0.27		
0.0114	95.9	0.0228	0.35	1.47	0.0494	0.0439	0.54	0.49	−0.94?
			1.00	1.50	0.0513	0.0524	0.49		
			1.50	1.56	0.0556	0.0569	0.35		
	0.0266		2.25	1.65	0.0621	0.0612	0.23		
0.0114	59.6	0.0205	0.33	1.13	0.0261	0.0260	0.95	0.46	−0.80
			1.00	1.21	0.0300	0.0312	0.50		
			1.50	1.27	0.0330	0.0337	0.35		
	0.0158		2.25	1.36	0.0379	0.0364	0.21		
0.0262	58.8	0.00392	0.40	2.80	0.0308	0.0320	0.99	0.45	−0.84
			1.00	3.11	0.0380	0.0381	0.44		
	0.0156		2.00	3.41	0.0455	0.0446	0.24		
0.0262	46.4	0.00377	0.30	2.34	0.0206	0.0235	1.92	0.59	−0.95
			0.60	2.55	0.0245	0.0268	0.91		
			1.00	2.70	0.0275	0.0296	0.56		
	0.0121		2.00	2.95	0.0328	0.0346	0.31		
0.0262	37.8	0.00367	0.70	2.18	0.0175	0.0220	1.47	0.96?	-1.28?
			1.25	2.38	0.0208	0.0249	0.73		
	0.0097		2.00	2.59	0.0246	0.0277	0.39		
0.0262	15.1	0.00326	0.30	1.53	0.0076	0.0074	0.92	0.35	−0.86
			0.60	1.65	0.0089	0.0084	0.51		
			1.00	1.73	0.0098	0.0093	0.36		
	0.0038		2.00	1.95	0.0124	0.0109	0.17		
0.0691	179.8	0.000770	0.33	14.3	0.1575	0.139	0.68	0.32	−0.77
			1.00	16.5	0.2100	0.181	0.34		
			1.50	17.5	0.236	0.204	0.22		
	0.0550		2.25	18.4	0.261	0.227	0.17		
0.0691	77.2	0.000591	0.37	10.0	0.0591	0.0545	0.71	0.34	−0.75
			1.00	11.4	0.0770	0.0693	0.33		
			1.50	12.2	0.0880	0.0777	0.23		
	0.0210		2.25	12.9	0.0984	0.0868	0.17		
0.0691	18.3	0.000489	0.50	5.3	0.0138	0.0128	0.57	0.38	−0.66
			1.00	5.7	0.0159	0.0152	0.38		
	0.0046		2.00	6.25	0.0192	0.0185	0.23		

figures in column V. For the reasons already given, no correction for radiation was made.

In column VIII are given the values of B, calculated as follows:

The value of **s** is found (equation **1**) by dividing **W** (column VI) by $(\varphi_2 - \varphi_1)$ (column II). From a curve of equation (**3**) drawn from data in the previous paper, the value of $\frac{a}{B}$ corresponding to the given value of **s** was found. This quantity divided into a, the diameter of the wire (column I), gives B (column VIII).

It was thought that B would be found to vary in inverse proportion to the pressure. In the previous paper the hypothesis was advanced that B would vary proportionally to the viscosity and in inverse proportion to the density of the gas. This, however, was not very well borne out by experiments in hydrogen and mercury vapor. According to this hypothesis, B should vary inversely with the first power of the pressure, for the viscosity is independent of the pressure.

It will be observed, however, that the product obtained by multiplying together the values in columns IV and VIII shows a very distinct tendency to increase with the pressure. The quantity B was therefore plotted on logarithmic paper, as a function of P, with the result that the points were found in nearly every case to lie in straight lines. For each of the experiments with a wire at any given temperature, a straight line was drawn in this way. The ordinate of these lines for a pressure of one megabar was read off and is given in Table I, in column IX. The slope of the straight line, n, is given in column X. The fact that the logarithmic plots gave practically straight lines means that B varies with the nth power of the pressure. The values of n in the different experiments do not show any distinct tendency to vary either with a or with the temperature. By a careful study of the curves, the most probable value of n was thought to be about - 0.75. It is true that the average of the values of n is numerically larger than 0.75, but the sets of experiments which seem to be most free from experimental error give values close to this.

To test the accuracy of this conclusion, the figures in column VII were calculated, based on the following assumptions:

1. The thickness of the plane film, B, for air at room temperature and 760 mm. pressure, is 0.43 cm. This is the value found from the experiments on platinum wires described in the previous paper.

2. That B varies inversely as the 0.75th power of the pressure (P). At a pressure of 1 megabar B would be 0.436 cm.

By aid of the above assumptions, the values of B were calculated, and from these the ratios $\frac{a}{B}$; then **s** was found by the plot of (**3**), and this was multiplied by $(\varphi_2 - \varphi_1)$ (column II), to obtain " **W** calc. " in column VII.

The agreement between the calculated convection and that observed by Kennelly is strikingly good. The only serious discrepancy between the two occurs with the largest wire at the highest temperature. This discrepancy may perhaps largely be accounted for by radiation. A "black" wire of 0.069 cm. diameter at a temperature of 179 deg. above room temperature would radiate about 0.050 watts per cm. A polished copper wire would radiate only about 0.001 watt, but if the surface is slightly oxidized or tarnished, it might easily radiate much more. The difference between the calculated and observed watts is only about 0.025, so that if the wire should radiate 50 per cent as much as a black body this difference would be accounted for.

It is interesting to note that with only two empirically determined constants, the equation (**1**) allows a much closer calculation of **W** than did Kennelly's equation with its four empirical constants.

KENNELLY'S DATA ON FORCED CONVECTION

By forced convection Kennelly means the convection of heat from a wire which is moving rapidly relatively to the surrounding air.

Kennelly's results on forced convection are given in two logarithmic plots. In one the amperes are plotted against the wind velocity and in the other the watts per cm. of length are plotted against wind velocity. He has corrected the watts as before for radiation, but in this case the loss by convection is so great that the radiation correction is small enough to be quite negligible. Therefore I have taken Kennelly's results for the watts directly and have not calculated them from the amperes, as in the case of free convection. Table II gives a summary of Kennelly's experimental data.

The third and fourth columns were obtained, as before, by drawing smooth curves as nearly as possible through the points given by Kennelly, without any reference to the straight lines

TABLE II
KENNELLY'S EXPERIMENTS ON FORCED CONVECTION

I	II	III	IV	V	VI	VII	VIII
Diameter of wire cm.	T_2-T_1 and $\phi_2-\phi_1$	Wind velocity $\frac{\text{cm.}}{\text{sec.}}$	**W** obs. $\frac{\text{watts.}}{\text{cm.}}$	**W** calc. $\frac{\text{watts.}}{\text{cm.}}$	B $\times 10^3$ cm.	B_{900} obs. $\times 10^3$	B_{900} calc. $\times 10^3$
0.0101	106	520	0.220	0.222	10.0	6.55	6.56
		900	0.280	0.281	6.55		
	0.0298	1800	0.388	0.390	3.90		
0.0101	179	400	0.320	0.350	16.0	8.1	7.29
		900	0.466	0.485	7.8		
	0.0550	1800	0.650	0.671	4.65		
0.0101	252	400	0.486	0.502	15.9	8.4	8.02
		900	0.690	0.693	8.13		
	0.0830	1800	0.960	0.950	4.75		
0.0159	117	330	0.250	0.262	15.5	7.1	6.68
		900	0.408	0.415	6.89		
	0.0335	1800	0.590	0.596	4.05		
0.0159	211	330	0.490	0.487	16.2	7.6	7.60
		900	0.760	0.757	7.68		
	0.0670	1800	1.100	1.079	4.45		
0.0159	305	330	0.720	0.735	18.5	8.5	8.55
		900	1.130	1.122	8.46		
	0.1060	1800	1.600	1.590	4.99		
0.0204	51	800	0.217	0.200	5.81	5.9	6.00
		1300	0.252	0.260	4.75		
	0.0134	1800	0.314	0.315	3.60		
0.0204	128	210	0.297	0.274	17.6	6.3	6.78
		400	0.380	0.362	11.45		
		900	0.570	0.536	6.25		
	0.0370	1800	0.810	0.788	3.89		
0.0204	206	210	0.475	0.453	20.8	7.2	7.56
		400	0.620	0.596	13.0		
		900	0.910	0.896	7.16		
	0.0650	1800	1.280	1.280	4.48		
0.0204	283	210	0.660	0.642	23.4	7.9	8.33
		400	0.880	0.835	14.0		
		900	1.260	1.215	7.96		
	0.0965	1800	1.780	1.758	4.87		

plotted by him. The figures in columns III and IV of the table represent simply three or four well-distributed points taken from these curves.

The thickness, B, of the plane film (column VI) was calculated similarly to B in Table I.

It is seen that B decreases as the wind velocity increases. To study the law with which this varies, B was plotted against V on logarithmic paper and a series of parallel straight lines was obtained. The slope of these lines was -0.75. In other words, B varies inversely as the 0.75th power of the wind velocity.

The ordinates of these straight lines corresponding to the abscissa $V = 900$ are given in column VII.

It is seen that B_{900} increases distinctly as the temperature difference $T_2 - T_1$ increases. But it apparently does not perceptibly depend on the diameter of the wire. By plotting B_{900} against $T_2 - T_1$ it was found that the following equation gives a fairly good approximation of B_{900}

$$B_{900} = 0.0055 + 0.000010\,(T_2 - T_1) \tag{7}$$

Column VIII gives the values of B_{900} calculated from this formula.

In the case of free convection, it will be remembered that B was found to be independent of the temperature T_2 of the wire, even up to the melting point of platinum. The reason that the temperature enters here is probably that with forced convection the viscosity of the inner and hotter portions of the gas film is a factor determining the thickness of the film, whereas in the case of free convection only the viscosity of the outer portions is of importance. Between the temperatures 300 deg. and 600 deg. K, the temperature coefficient of the viscosity, $\mathbf{h}$, is 0.00219, whereas the temperature coefficient of B_{900} is $0.00001 \div 0.0055 = 0.00180$, or about 83 per cent of that of the viscosity. In other words, for forced convection B is approximately proportional to the viscosity of the gas at a point $\frac{1}{6}$ of the way from the surface of the wire to the outer edge of the film.

The values of **W** given in column V were calculated by first determining B for the wind velocity given in column III by means of the relation

$$\frac{B}{B_{900}} = \left(\frac{900}{V}\right)^{0.75} \tag{8}$$

From this value of B, **W** was calculated in the usual way.

If we assume that equation (8) holds down to very low velocities and substitute for B the value 0.43 cm. found for free convection and for B_{900} the value from (7), we find for the velocity V_0 which exists in free convection

$$V_0 = 2.7\,[1 + 0.0024\,(T_2 - T_1)] \text{ cm. per sec.}$$

Kennelly had concluded from his observations that the energy loss from the wires varied directly as the square root of the wind velocity. According to the present theory this could only occur for wires of a certain size.

In case the diameter of the wire is large compared to the film thickness B, we should expect the energy to be inversely proportional to B; that is, directly proportional to the 0.75th power of the wind velocity. For wires of smaller size the energy would vary less rapidly with the wind velocity, so that for wires of a certain size it would vary approximately with the square root of the wind velocity.

Kennelly's experiments cover only such a narrow range of sizes of wire that his data furnish no way of testing this deduction from the theory. But it should be pointed out that many other observers have concluded in experiments on the rate of solutions of solids in liquids and other similar phenomena, that the thickness of the diffusion film varies inversely as the 0.70th or 0.75th power of the rate of stirring. As far as I know however, the case where the size of the wire is small compared to thickness of the film has not been handled.

SUMMARY

Kennelly's data on *The Convection of Heat from Small Copper Wires* afford strong proof of the reliability and usefulness of the author's theory of convection. According to this theory, " convection " consists essentially in conduction of heat through a film of gas of definite thickness, in which the heat carried by motion of the gas is negligible compared to that carried by conduction, and outside of which the temperature is maintained uniform because of convection currents. The thickness of the film of gas is related in a simple way to the diameter of the wire, so that from the experiments the thickness B, which the film would have in case of a plane surface, can be readily calculated.

Previous results of the author have shown that

1. The quantity B, for quiet air at room temperature and one atmosphere pressure, is equal to 0.43 cm.

2. *B* is independent of the temperature of the wire, from room temperature up to the melting point of platinum, 1750 deg. cent.

3. The values of *B* obtained from experiments on wires of different sizes are found to be the same.

In the present paper it is shown that Kennelly's results confirm the above conclusions and furthermore lead to the following new conclusions:

4. The film thickness (for plane surface) *B* varies inversely as the 0.75th power of the pressure of the gas.

5. The value of *B* varies inversely as the 0.75th power of the wind velocity.

6. Although for free convection, *B* was found independent of the temperature of the wire, it is found that for forced convection *B* increases slightly with the temperature. See equation (7).

7. For forced convection, however, the value of *B* is found independent of the diameter of the wire, just as in the case of free convection.

8. Radiation from small metallic wires is practically negligible compared to convection, up to temperatures of several hundred degrees.

In a series of subsequent papers[6] it will be shown that

1. The value of *B* increases approximately proportionally to the absolute temperature of the atmosphere surrounding the wire, even when the latter varies from −190 deg. to 300 deg. cent.

2. The value of *B* found from actual experiments on the convection from plane surfaces agrees excellently with the value found from small wires. In the case of plane surfaces, however, the radiation loss is usually much greater than that by convection, so that a careful study of the radiating properties of the surface has to be made. It will be shown that the convection losses from cylinders of any size, as well as from plane surfaces, can be accurately calculated from the formulas given in this paper.

3. In the case of convection between two surfaces (for example, between two concentric cylinders or two boxes one in the other), the theory of the conducting film proves extremely useful and makes it possible to calculate nearly all simple cases of heat convection with reasonable accuracy.

These papers will also contain evidence of many kinds which will clearly indicate the significance of the conducting film.

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[6] The first of these will appear in the *Trans. Amer. Electrochemical Soc.*, Vol. 23, (1913).

DISCUSSION ON "METALLIC TUNGSTEN AND SOME OF ITS APPLICATIONS" (COOLIDGE), AND "THE CONVECTION AND CONDUCTION OF HEAT IN GASES" (LANGMUIR), BOSTON, MASS., JUNE 25, 1912.

C. M. Green: Dr. Weintraub of the research laboratory at Lynn has suggested a new use of tungsten, that is as a substitute for platinum leading-in wire for rectifier tubes. I am thoroughly satisfied from experiments I have made that it will be better than platinum. The specific resistance is about one-half that of platinum, or about 5 to 6 microhms per cu. cm., while the platinum which we use at the present time is about 13 to 14 and the platinum used a few years ago had a specific resistance of 30 to 40 microhms.

A Member: I was very much interested in Mr. Coolidge's paper and I tried in the first instance to see if the tungsten could be plated with copper. I was interested in his statement that it could be wet with copper, and I would like to inquire if he has ever tried to find out whether the metal could be plated with copper, because, if it could, it would be very easy to solder it to other metals.

William J. Hammer: I would like to ask Mr. Coolidge whether he has observed any special changes in the characteristics of tungsten while it is being gradually heated. I recall that in Mr. Edison's very early experiments at Menlo Park, whereas his platinum would only give a light of say from three to four candle power before it melted, by gradually putting little increments of current through the platinum the occluded gases were driven out and the metal was made more dense and became so hard that a sharp file would not mark it, and in this condition the platinum could be brought up to an incandescence of from 30 to 34 candles without melting. Mr. Edison also alloyed the platinum with iridium in many of his lamps.

Carl Hering: I would like to ask Mr. Coolidge how the tungsten acts when used as electrodes, and whether it will stand the oxidizing influence in being used as an anode in ordinary electrolysis.

W. D. Coolidge: The question has been raised as to whether tungsten could be plated with copper. That is possible and fairly easy, and it is possible to go ahead as suggested and solder such a copper-plated piece of tungsten. That method we have not found so satisfactory as the method we are now using with molten copper, the adhesion not being anywhere near so firm as we get from the present method. The plating goes best in a copper sulphate solution. Mr. Hammer raised a question about occluded gas. We have done a great deal of work along this line and have found that the greater part of the gas which is in the drawn wire comes off very quickly when the wire is heated in a vacuum. Dr. Hering raises the question of whether tungsten can be used as an anode for electrolysis. As a matter of fact tungsten is oxidized and goes into solution very readily indeed under such conditions. We had hoped that it could be used in place of platinum.

H. M. Hobart: In the latest edition of the A. I. E. E. Standardization Rules, paragraph 269 relates to the application of temperature corrections to take into account the room temperature on the occasion of tests and to permit of arriving at values corresponding to the reference room temperature of 25 deg. cent. The rule is based on the assumption that the observed temperature rise will be greater the higher the temperature of the surrounding air. My experience does not conform to this rule, but shows rather that the *temperature rise* will generally be *less*, the higher the temperature of the surrounding air. It is very important to engineers that any uncertainty in this matter should be cleared up and I should be pleased if Dr. Langmuir would give us the advantage of his experience and opinions bearing upon this point.

If an electrical machine is to be operated in a place where the surrounding temperature is likely to be high, say 40 deg. cent., then it is very important to be able to know in advance whether a certain machine, tested at, for example, 20 deg. cent., and then sustaining a temperature rise of 40 deg. cent., will, under the conditions of its practical operation in the hot location, have a rise of 44 deg. cent., or only, say, 38 deg. cent. At present the data are very conflicting, and some engineers would be of the opinion that the rise when the surrounding temperature is 40 deg. cent. would amount to 44 deg. cent., thus bringing the temperature of the machine to 84 deg. cent., while the tests to which I allude would indicate that the rise would be somewhere between 36 deg. and 40 deg. cent., say 38 deg. cent., thus making the actual temperature of the machine, when the surrounding atmosphere is 40 deg. cent., only some 78 deg. cent.

Any information which Dr. Langmuir could furnish in this matter would be of much value.

Irving Langmuir: In reply to Mr. Hobart's question, I would like to point out that there are apparently only two factors involved in convection: first, the heat conductivity of the air, and second, the thickness of the film which determines the shape factor. In quiet air this shape factor can be calculated in the cases of wires and plane surfaces. However, in other cases (as where several wires are close together or where we have a confined space, such as might exist in the armature of a dynamo) this shape factor would be difficult to calculate, but in any case it is probably nearly independent of the temperature, and we may say that the heat convection would vary with the temperature practically only because of the temperature coefficient of the heat conductivity of the air itself. Since the latter nearly doubles with the 300 deg. rise in temperature, it is apparent that the convection should increase with increase in temperature of the air in which convection takes place.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 25, 1912.

CHARACTERISTICS AND APPLICATIONS OF VIBRATION GALVANOMETERS

BY FRANK WENNER

In the vibration galvanometer we have a type of synchronous motor which is distinctly different from all the ordinary types of dynamo-electric machines. Further, it does not have any of the characteristics of any of the ordinary galvanometers, and except for the fact that it is used in the detection or measurement of small currents and voltages, it should not be called a galvanometer. In galvanometers, except when used in the measurement of transient currents or quantity of electricity, the moving system is displaced until we have an equality of static couples acting on it. In the vibration galvanometer the equilibrium condition is an equality between integral values of the product of the current and generated voltage and the mechanical power dissipated in various ways as in ordinary electric motors when operated without a load. It therefore behaves more like an electric motor than like a galvanometer. Further, since it is used only with alternating currents and operates in synchronism with the current it must necessarily have some of the characteristics of a synchronous motor. As a motor the efficiency of conversion was found in a particular case to be as high as 97½ per cent, while the power required to maintain an easily discernible amplitude of vibration was of the order of 10^{-11} watts. One of the large turbo-generators would therefore furnish the power necessary to operate a thousand-million-billion such machines.

While the vibration galvanometer will probably never be used in the ordinary way for driving other machines, it is of considerable interest from a theoretical standpoint and possesses certain characteristics which make it a most valuable instrument for use in a large number of alternating-current measurements.

A number of different forms of galvanometers have been and are being used. One form is very similar to an oscillograph except that in general the period is longer and the oil for damping is omitted. Another form is very similar to the D'Arsonval galvanometers of the marine type except that the coil is narrower and the suspensions tighter. In all cases provision is made for changing the period of the moving system. This is usually done by changing the length or tension of the suspensions. Where a large range in frequency is desired the suspensions are often made bifilar.

Passing an alternating current through the coil causes it to vibrate back and forth past its equilibrium position, hence the name vibration galvanometer. The amplitude of the vibration, which is a measure of the current, is ordinarily determined by observing the broadening of a line image as seen in a small mirror attached to the moving system. As regularly used in the detection or measurement of current or voltage the natural or free frequency of the moving system is made to correspond with the frequency of the alternating current to be detected. As a result the amplitude of the vibration is much larger than it would be under almost any other condition.

The sensitivity is large only to currents of the frequency to which the moving system of the galvanometer is tuned. It is therefore possible to use currents of almost any wave form, even in those null methods in which an exact balance can be obtained only with a current free from all higher harmonics. In all such measurements we may make our observations and calculations just as if we were using current having a sine wave form, since the galvanometer responds only very feebly to the 3rd, 5th and higher harmonic components. It is this characteristic combined with its extremely high sensitivity at low frequencies which makes the vibration galvanometer a most valuable instrument in various kinds of alternating-current measurements.

Before we can make much progress in the design of an instrument or machine it is necessary that we know definitely the relation between its various constants. In some cases this knowledge is necessary before we can even use a well designed and constructed instrument or machine to its best advantage. We shall therefore show the relation which exists between the amplitude of the vibration and the impressed voltage in terms of the intrinsic constants of the instrument and of the electric circuit in which it may be used. Since here we have a mechanical and an electrical oscillating system so connected that they must necessarily operate at the same frequency, we shall make free use of the analogy existing between such systems. Passing a current through the winding produces a mechanical torque tending to displace the moving system of the galvanometer from its equilibrium position. The torque is proportional to the current and we shall let G be the proportionality factor or the displacement constant. In addition we shall use the following notation, in which vectors are designated by bold-faced type, and make use of the following well-known relations:

IN THE ELECTRICAL SYSTEM	IN THE MECHANICAL SYSTEM
L = inductance	K = inertia constant
r = electrical resistance	D = damping constant or mechanical resistance
C = capacity	U = restoring constant analogous to $1/C$
e' = impressed voltage	$G\mathbf{i}$ = displacing torque
$\mathbf{i}$ = current	s = rate of displacement or angular velocity
q = charge = $\int \mathbf{i}\,\delta t$	ϕ = displacement = $\int s\,\delta t$

$$e' = E'\,\epsilon^{ipt} \tag{1}$$

$$G\mathbf{i} = G\,I\,\epsilon^{ipt} \tag{2}$$

$$\mathbf{i} = I\,\epsilon^{ipt} \tag{3}$$

$$s = S\,\epsilon^{ipt} \tag{4}$$

$$q = Q\,\epsilon^{ipt} \tag{5}$$

$$\phi = \Phi\,\epsilon^{ipt} \tag{6}$$

$$I = \frac{E}{r + i\,(p\,L - 1/C\,p)} \tag{7}$$

$$S = \frac{G\,I}{D + i\,(K\,p - U/p)} \tag{8}$$

or, if we let X represent the electrical reactance and M represent the mechanical reactance,

$$I = \frac{E'}{r + i X} \tag{9}$$

$$S = \frac{G\,I}{D + i\,M} \tag{10}$$

$$Q = \frac{E'}{i\,p\,(r + i\,X)} \tag{11}$$

$$\Phi = \frac{G\,I}{i\,p\,(D + i\,M)} \tag{12}$$

Here E' is the total voltage available for producing current or the sum of the impressed voltage E and generated voltage E_g.

The voltage generated by the relative motion of the magnet and winding is proportional to the amplitude and in quadrature with the vibration. It is also proportional to the frequency and proportional to the displacement constant, and it is easily shown that

$$E_g = -ipG\Phi \tag{13}$$

therefore

$$I = \frac{E - ipG\Phi}{r + iX} \tag{14}$$

This value of I substituted in equation (**12**) gives

$$\Phi = \frac{GE}{p\left[(-rM - DX) + i(Dr - MX + G^2)\right]} \tag{15}$$

or

$$\Phi = \frac{GE}{p\sqrt{(-rM - DX)^2 + (Dr - MX + G^2)^2}} \tag{16}$$

or

$$\phi = \frac{GE\epsilon^{i(pt+\alpha)}}{p\sqrt{(-rM - DX)^2 + (Dr - MX + G^2)^2}} \tag{17}$$

where.

$$\tan\alpha = \frac{(Dr - MX + G^2)}{Mr + DX} \tag{18}$$

Equation (**16**) gives the relation between the amplitude of the vibration, the impressed voltage, the displacement constant, the frequency, and the other constants of the electric and mechanical systems expressed as resistances and reactances.

Where the instrument is to be used in precise measurements we usually desire as high a sensitivity as can conveniently be obtained, *i.e.* we wish as large an amplitude of the vibrations for a given small impressed voltage as we can conveniently get.

An inspection of equation (**16**) does not at once suggest the relations which should be made to exist between the various quantities D, r, M, X, and G to give the best sensitivity. Since power is absorbed or converted into heat proportional both to D and to r, the most natural beginning is to make both small. The mechanical resistance or damping constant D is a definite constant of the galvanometer, and as we shall see later, one of the most important points to be looked to, both in the design and the construction, is to make this constant as small as possible.

The electrical resistance r is the total resistance of the circuit in which the galvanometer is used. As the resistance of a part of this circuit is usually fixed from other considerations, the particular value of the resistance of the galvanometer is of little importance, provided it is less than say $\frac{1}{4}$ the total resistance of the circuit.

As vibration galvanometers are usually constructed, provision is made for varying the free period of the moving system so that the mechanical reactance can be adjusted to zero for any frequency in the range over which it is expected that the galvanometer will be used. The electrical reactance is usually very small in comparison with the electrical resistance. It can, however, be varied by placing capacity or inductance in series with the winding of the galvanometer.

If the galvanometer is so constructed that the displacement constant G can be varied (and all instruments intended for use in circuits of different resistances should, if a high sensitivity is desired, be so constructed), we can then adjust each or all of the remaining quantities, the electrical reactance X, the mechanical reactance M, and the displacement constant G. If M is adjusted to zero and if X is small or adjusted to zero it will be seen that the sensitivity is a maximum when

$$G^2 = Dr$$

Under these conditions we have

$$\Phi = \frac{E}{2\, p \sqrt{Dr}} \tag{19}$$

or, since we observe the total amplitude of the vibration and measure the root-mean-square value of the voltage,

$$\Phi = \frac{E}{p \sqrt{2\, Dr}} \tag{20}$$

as has been shown by the author.[1]

Under these conditions the generated voltage is half as large as and in direct opposition to the impressed voltage. This we know to be the condition under which the mechanical power developed is a maximum. This, then, is a condition which gives the maximum sensitivity with the particular values of r and D.

Since to get the maximum sensitivity it is only necessary to make such adjustments as will bring the generated voltage in direct opposition to and make it half as large as the impressed voltage, it should be possible to bring about this condition by

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[1] *Bulletin*, Bureau of Standards, Vol. VI, p. 376; reprint 134; 1909.

changing any two of the three constants X, M, and G. If these constants are changed one after the other in small steps or continuously it can be shown by differentiation that the sensitivity becomes a maximum for changes

$$\text{of } X\text{, when } X = \frac{G^2 M}{D^2 + M^2} \tag{21}$$

$$\text{of } M\text{, when } M = \frac{G^2 X}{r^2 + X^2} \tag{22}$$

$$\text{and of } G\text{, when } G = \sqrt[4]{(r^2 + X^2)\,(D^2 + M^2)} \tag{23}$$

Since the last of these equations is the product of the other two, it follows that if any two of the constants are adjusted so that they simultaneously have their best value, the third constant also has its best value, or the sensitivity is the maximum attainable. When this adjustment, which is a double one, and in some cases will have to be made by successive approximations, is carried out, we have

$$\frac{X}{r} = \frac{M}{D} \tag{24}$$

or the electrical time constant equal to the mechanical time constant,

$$\text{and} \qquad \frac{r\,G^2}{r^2 + X^2} = D \tag{25}$$

or the electromagnetic damping equal to the mechanical damping.

A substitution first of the value of G as given by equation (**25**) and then of the value of X as given by equation (**24**), in equation (**16**), shows that, even with an inductive circuit,

$$\Phi = \frac{E}{2p\sqrt{Dr}} \tag{26}$$

as given above, and as has been shown recently by Butterworth.[2]

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[2] *Proceedings Phys. Soc.*, London, Vol. XXIV, p. 77, 1912.

If we express the amplitude of the vibration in terms of the broadening of the line image one meter from a mirror attached to the moving system, the voltage in microvolts, the resistance in ohms and the mechanical constants in c.g.s. units, then

$$\Phi = \frac{2.0\,E}{f\,\sqrt{Dr}} \qquad (27)$$

when f is the frequency, or if v is the sensitivity the ratio of the number representing the amplitude of the vibration to the number representing the voltage

$$V = \frac{2.0}{f\,\sqrt{Dr}} \qquad (28)$$

Since usually it is not practical to place a variable inductance in series with the galvanometer and by adjusting it and the mechanical reactance to bring about the best condition, and since few of the galvanometers now in use are provided with a means for adjusting G, we are often obliged to be content with the best condition we can obtain by the adjustment of the free frequency only. If this adjustment is made and the electrical reactance is small in comparison with the electrical resistance, then equation (**16**) takes the form

$$\Phi = \frac{G\,E}{p\,(Dr + G^2)} \qquad (29)$$

and these are the relations under the more usual conditions of use.

To the person who is considering using a vibration galvanometer the question as to what sensitivity can readily be obtained is of much more importance than the effect of various constants upon the sensitivity. In this connection we may state that three years ago the author determined the constants of three vibration galvanometers and found the voltage sensitivity in millimeters per microvolt at 100 cycles as follows:

0.0014, 0.0061 and 0.0075.

Recently Mr. Silsbee of the Bureau of Standards made, according to the suggestions of the author, a new coil for one of the older galvanometers of the D'Arsonval type, in fact one of the three just mentioned. With the new coil the voltage sensitivity at 25 cycles is 0.47. The instrument was designed for use in a bridge having a resistance of about one ohm. It has since been found that it will be necessary to increase the resistance in the bridge arrangement so that the total resistance of the galvanometer circuit will be about four ohms. Under these conditions the sensitivity will be 0.28, while if the magnet is strengthened just a little so as to give the best conditions the sensitivity will be 0.40. With the new coil the galvanometer differs in so many ways from the others that the relative merits cannot be represented by figures giving the ratio of the voltage sensitivities which range from 60 to 300. It cannot be used at a frequency of 100, neither can the others be used at a frequency of 25. It was designed to operate at the lower frequency and to be used in connection with a low-resistance bridge. When so used its sensitivity is about the same as that of a good direct-current D'Arsonval galvanometer designed for and used in connection with a bridge of the same resistance.

We have gone rather fully into the matter of the sensitivity and the adjustments necessary to get the maximum sensitivity attainable with any particular galvanometer when used in any particular circuit. We have done this because the matter is one of considerable importance to many of those working with such instruments and a matter which seems not to be very well understood.

A further consideration of equation (16) will bring out other characteristics of the vibration galvanometer. In cases where the electrical reactance is small in comparison with the resistance so that it need not be considered, we have

$$\Phi = \frac{G\,E}{p\,\sqrt{r^2\,M^2 + (Dr + G^2)^2}} \qquad (27)$$

or since $M = p\,K - U/p$ and $U = p_0^2\,K$, where p_0 is the free frequency of the moving system,

$$\Phi = \frac{G\,E}{r\,\sqrt{K^2\,(p_0^2 - p^2)^2 + p^2\,(Dr + G^2)^2/r^2}} \qquad (28)$$

If $p_0 = p$

$$\Phi = \frac{G\,E}{p_0\,(Dr + G^2)} \text{ or } V_0 = \frac{G}{p\,(Dr + G^2)} \qquad (29)$$

If p_0 is very different from p, $K(p_0^2 - p^2)$ is large in comparison with $p(Dr + G^2)$, so we may write

$$\Phi = \frac{GE}{\pm rK(p_0^2 - p^2)} \text{ or } V = \frac{G}{\pm rK(p_0^2 - p^2)} \qquad (30)$$

or we have

$$\frac{V_0}{V} = \pm (f_0 - f^2/f_0) \frac{2\pi Kr}{Dr + G^2}$$

If the galvanometer has an inertia constant of 0.02, a damping constant of 0.01 and a displacement constant of 10,000 (none of which are exceptional values), then

$$\frac{2\pi Kr}{Dr + G^2} = 6.3, \text{ if } r = 100 \text{ ohms } (10^{11} \text{ c.g.s. units})$$

or

$$12.6, \text{ if } r \text{ is large.}$$

Then if the fundamental frequency of the voltage is 60 and the instrument is tuned to this frequency a substitution of 60 for f_0 and of 180 and 300 for f gives the ratio of the sensitivity of the instrument to the fundamental as compared with its sensitivity to the 3rd and 5th harmonic, as follows:

With 100 ohms	With high resistance
$S_1/S_3 = 3000$	or = 6000
$S_1/S_5 = 9000$	or = 18,000

If the instrument is tuned to the 3rd or 5th harmonic a substitution of 180 and 300 for f_0 and 60 for f gives the ratio of the sensitivity to the harmonics as compared with its sensitivity to the fundamental, as follows:

With 100 ohms	With high resistance
$S_3/S_1 = 1000$	or = 2000
$S_5/S_1 = 1650$	or = 3300

It will thus be seen that the galvanometer when tuned to the fundamental is (if the resistance of the circuit is 100 ohms or more) at least 3000 times as sensitive to the fundamental as to any of the harmonics. If, then, the voltage used in testing has a third and higher harmonics amounting to not more than 3 per cent, the accuracy to which a balance may be established cannot be limited by the presence of unbalanced harmonic components of the voltage, unless the accuracy sought is better than 1 in 100,000. It is this characteristic of not responding to the harmonic components of the current passing through it, together with its high sensitivity to the fundamental component both of the voltage and current, which has led to the use of the vibration galvanometer in various alternating-current measurements.

It will also be seen that where a galvanometer having the constants just considered is tuned to a frequency of three or five times the fundamental, and the resistance is high, the instrument is 2000 or more times as sensitive to the harmonics as to the fundamental. The instrument can therefore be used to read the harmonic components of the voltage directly from the amplitude of the vibration and it should be possible, if the harmonics are small, to obtain their values to better than 0.1 per cent of the fundamental. In this method of determining the higher harmonic components of the electromotive force use is made of the mechanical resonating system of the galvanometer instead of an electrical resonating system.

If the frequency of the impressed voltage is varied from below that for which the amplitude of the vibration is a maximum to above this value the angle between the generated and impressed voltage changes by nearly π radians or 180 deg. The change in angle with frequency is largest at the frequency which gives the maximum amplitude. In some cases we have a noticeable change in the phase angle when the frequency changes by only a few hundredths per cent. Considerably below the particular frequency the current lags behind the impressed voltage by a large angle, and considerably above this frequency it leads by a large angle.

If then the stator windings of a very small two-phase induction motor were connected to the same voltage supply, one through a resistance and the other through a large vibration galvanometer, we would have, in general, an elliptical rotating field at the stator and the direction of rotation would depend upon whether the frequency of the impressed voltage were above or below that for which the amplitude of the vibration of the galvanometer would be a maximum. It is not at all improbable that such an arrangement might be used to accomplish some particular end in connection with the generation or transmission of electrical power, such for example as the indication or regulation of the frequency.

A definite expression for the phase angle between the impressed voltage and the current may be obtained by eliminating ϕ from equations (**12**) and (**14**). This gives

$$\mathbf{I} = \frac{\mathbf{E}\,[G^2D + r\,(M^2 + D^2) \; - i\,(X\,(M^2 + D^2) \; - MG^2)]}{[G^2 + r\,D - M\,X]^2 + [X\,(M^2 + D^2) - M\,G^2]^2} \qquad \textbf{(31)}$$

or

$$\mathbf{i} = \frac{\mathbf{E}\;\sqrt{[G^2D + r\,(M^2 + D^2)]^2 + [X\,(M^2 + D^2) \; - M\,G^2]^2}\;\epsilon^{i\,(pt - \beta)}}{[G^2D + r\,D \; - M\,X]^2 + [X\,(M^2 + D^2) \; - M\,G^2]^2} \qquad \textbf{(32)}$$

where

$$\tan\,\beta = \frac{X\,(M^2 + D^2) - M\,G^2}{r\,(M^2 + D^2) + D\,G^2} \qquad \textbf{(33)}$$

When adjustments have been made so that equations (**24**) and (**25**) are satisfied,

$$I = \frac{E}{2\,r} \cdot \frac{r^2 + X^2}{r} \qquad \textbf{(34)}$$

and

$$\beta = 0 \qquad \textbf{(35)}$$

That is, under the best conditions the current is in phase with the impressed voltage.

In engineering work the vibration galvanometer is being used but little. When its characteristics become more widely known and when it becomes known that it is not a delicate instrument various uses will no doubt be found for it.

As a laboratory instrument we may mention that it is being used in the Bureau of Standards in connection with:

The Anderson bridge for the comparison of self-inductance with capacity and resistance.

One or more bridge methods for the comparison of self with mutual inductance.

Bridge method for the comparison of the capacities and phase angles of condensers.

Bridge methods for comparing the resistances and time constants of wire resistance standards.

The Thomson bridge method in the comparison of time constants and resistances, to alternating currents, of standards of low resistance.

In the determination of the ratio of transformation and the phase angle between primary and secondary voltages and currents of potential and current transformers.

It has also been used in various other precision measurements and the indications are that it will soon be used in still others.

In the National Physical Laboratory in England the vibration galvanometer is also being much used. Of the various applications there we may mention:

The absolute measurement of resistances by a two-phase alternating-current method.

The testing of transformer steel, using a null method for determining the total losses.

A modified Carey Foster method for comparing self and mutual inductance.

In most laboratories, however, the vibration galvanometer has met with less favor than it deserves.

DISCUSSION ON "CHARACTERISTICS AND APPLICATIONS OF VIBRATION GALVANOMETERS" (WENNER), BOSTON, MASS., JUNE 25, 1912.

Jefferson E. Kershner: What is the method of reading the instrument?

Frank Wenner: The ordinary method of reading the instrument is to use a mirror on the moving system, and an arrangement giving a line source of light. When the instrument is standing still the image that you get is in the form of a line. If an alternating current is passed through the instrument the image broadens.

Jefferson E. Kershner: Do you measure the width of the line?

Frank Wenner: The width of the line is an indication of the amplitude of vibration. The motion being slower at the ends, it seems to stand out, as two lines. Of course, you can read it from a pointer, but in most of the work in which the vibration galvanometer has been used they use a reflecting system.

W. H. Pratt: I would ask how rapidly the sensitiveness of the instrument is reduced as you depart from the ideal conditions outlined?

Frank Wenner: It all depends on what you want to do with the instrument, as the sensitiveness can be controlled in design. If you want to construct an instrument which will not respond to the harmonics, and you are going to use it at a very definite frequency, you can afford to reduce the range in frequency, to, say, one-tenth of a per cent at which it will operate. Then it practically does not respond at all to any of the harmonics. If, on the other hand, you want to use it at commercial frequencies, the instrument should be designed so that it has a very flat top sensitivity curve. The way this curve drops off has no connection at all with the maximum height of the curve. The sensitivity at the resonating frequency is independent of whether you make this curve steep or not.

W. H. Pratt: This last point you mentioned, about the width of the curve not being dependent on the maximum point, can that be controlled by the iron in the circuit? For instance, your iron in the inductive circuit of the instrument, having some hysteresis, would tend to broaden the range over which there was a resonant resistance. Does that have an appreciable effect?

Frank Wenner: No, I think not. The matter that affects the sharpness of this curve depends almost entirely on the mechanical constants of the instrument. It bears a little on the electrical constants of the circuit, but only slightly.

R. A. Gray: Is the instrument chiefly used as a deflection instrument or as a zero instrument?

Frank Wenner: It is used almost entirely as a zero instrument. It has been used to some extent as a deflection instrument and there is no reason why it cannot be so used. The deflections are as nearly proportional to the e.m.f. as they are in other deflection instruments.

Albert F. Ganz: By deflection, do you mean the width of the reflected band of light? Is that what measures the vibration?

Frank Wenner: Yes, that reflection can be brought back on the transparent scale and read in divisions.

George F. Sever: Up to what specific point can that band be used in connection with the sensitiveness of the reading and the accuracy of the reading of the instrument?

Frank Wenner: I have used it up to a few centimeters, but then only in determining some of the constants of the instrument, and was not, at that time, concerned with it as a deflection instrument. Ordinarily, the deflection is very small when it is used in the usual way.

N. Monroe Hopkins: Is the band quite distinct on the right and left edge respectively?

Frank Wenner: It is very distinct. When the band spreads out to considerable width it has this effect: it is very sharp on the extreme edges, and corresponding to the width of the filament of the lamp, or other source of illumination, it is comparatively bright, and from that it gradually shades off until you have nothing in the center.

John D. Ball: If the deflection is only a few centimeters is there not a correction for the width of the beam—the beam in zero position?

Frank Wenner: The source of the light that we ordinarily use is a filament from a lamp and focus it as sharply as possible. When you come to a very small deflection you might not be able to read it very definitely, and it would be necessary to read it not from the extreme edge, but from what corresponds to the center of the filament on each side of the image.

M. G. Lloyd: When you have the frequency adjusted to correspond with the natural frequency of the instrument, what relation is there between the deflection and current?

Frank Wenner: It is directly proportional either to the current or the voltage.

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TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JANUARY 1 TO JUNE 25, 1912

VOL. XXXI, PART I

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N. Y., U. S. A.
1912