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APPENDIX.

A paper presented at the 203d Meeting of the American Institute of Electrical Engineers, New York, January 26, 1906.

POWER PLANT ECONOMICS.

BY HENRY G. STOTT.

Three years ago the steam-power plant for the generation of electricity had apparently settled down to an almost uniform arrangement of standard apparatus in which one power plant differed from another only in details of construction of engines, generators, and auxiliaries. As only about twenty years had then elapsed since the first central station was put in operation on a commercial basis, this uniformity of design seemed to indicate that in the near future it would only be necessary to purchase a standard set of power-plant drawings, and make the necessary changes in size of units in order to have a station of the best type known to the art.

The internal combustion or gas engine had from time to time been brought forward as a candidate for the position of prime mover, with every prospect of improved economy in fuel consumption; but with the exception of a few special instances it was not looked upon with favor, as shown by the almost universal use of the steam engine.

After a long period of development a new factor in power-plant design; namely, the steam turbine, was placed on the market in commercial sizes. It is safe to say that during the last three years no other piece of apparatus has had so stimulating an effect upon the power plant. Its effect upon the entire plant has been most beneficial, for it has revived the apparently moribund superheater. This has now been so developed and improved that superheat of 200° or 300° fahr. can be safely and economically obtained. With the development of the superheater further study of the problem of combustion has improved the efficiency of the furnace; and this most important subject is apparently susceptible of still further development.

One other important result of the steam-turbine development has been the development of condensing apparatus to such a point of efficiency that a vacuum within one inch of the simultaneous barometer reading can now be maintained without difficulty.

Another change in the power plant has been the reversion to high-speed generators, resulting in decreased cost of the generator and its foundations, as well as saving in floor space.

Last but not least the steam turbine has put the reciprocating engine and the gas engine on the defensive and has actually been unkind enough to throw out hints in regard to the application of Dr. Osler's proposed methods to the treatment of older apparatus.

The reciprocating engine and internal-combustion engine have not been slow in accepting this challenge; they have responded by showing so improved an economy (especially in the gas engine) that the situation has become most interesting to the power-plant designer. It is safe to say that the developments of the next ten years will show very marked improvement in power plant efficiency.

In regard to this development the author wishes to direct attention to the basic fact that in power plants one should not look merely for increased efficiency in the prime mover, but should also investigate and analyze the entire plant from the coal to the bus-bars: first, in regard to efficiency; secondly, in regard to the effect of load-factor upon investment; and thirdly, the effect of the first and second upon the total cost of producing the kilowatt-hour, which is the ultimate test of the skill of the designer and operator.

EFFICIENCY.

In Table 1 will be found a complete analysis of the losses found in a year's operation of what is probably one of the most efficient plants in existence to-day and, therefore, typical of the present state of the art.

TABLE NO. 1.

ANALYSIS OF THE AVERAGE LOSSES IN THE CONVERSION OF ONE POUND OF COAL INTO ELECTRICITY.

	B.t.u.	%	B.t.u.	%
1. B.t.u. per pound of coal supplied....	14 150	100.0		
2. Loss in ashes....................			340	2.4
3. Loss to stack....................			3 212	22.7
4. Loss in boiler radiation and leakage..			1 131	8.0
5. Returned by feed-water heater......	441	3.1		
6. Returned by economizer...........	960	6.8		
7. Loss in pipe radiation..............			28	0.2
8. Delivered to circulator..............			223	1.6
9. Delivered to feed-pump.............			203	1.4
10. Loss in leakage and high-pressure drips			152	1.1
11. Delivered to small auxiliaries........			51	0.4
12. Heating..........................			31	0.2
13. Loss in engine friction..............			111	0.8
14. Electrical losses....................			36	0.3
15. Engine radiation losses.............			28	0.2
16. Rejected to condenser..............			8 524	60.1
17. To house auxiliaries................			29	0 2
	15 551	109.9	14 099	99.6
	14 099	99.6		
Delivered to bus-bar...........	1 452	10.3		

DISCUSSION OF DATA IN TABLE 1.

Item 1. *B.t.u. per Pound of Coal Supplied.* The thermal value of the coal used is evidently of prime importance, as it affects the cost efficiency of the entire plant. The method of purchasing coal used in the plant from which this heat balance is derived is that of paying for B.t.u. only, with suitable restrictions on the maximum permissible amount of volatile matter, ash, and sulphur.

A small sample of coal is automatically taken from each filling of the weighing hoppers, so that the final sample represents a true average of a boat-load of coal. This final average sample is then pulverized and tested for heat value in a bomb calorimeter, after which a proximate analysis is made of another portion of the sample. This method of purchasing coal has been in use for two years, with highly satisfactory results.

Item 2. *Loss in Ashes.* It is doubtful whether a further saving in this item can be made, as the extra care and labor necessary to accomplish any improvement would in all probability offset the saving in coal.

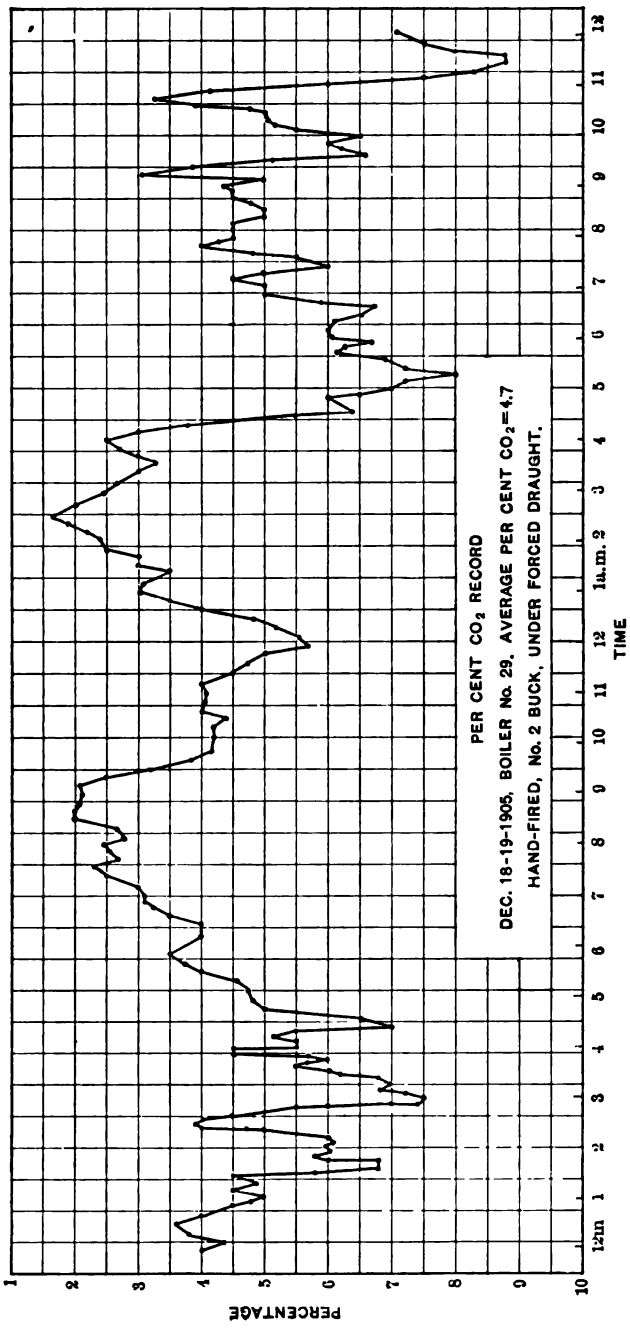
PER CENT CO_2 RECORD
DEC. 18-19-1905, BOILER No. 29. AVERAGE PER CENT CO_2=4.7
HAND-FIRED, No. 2 BUCK, UNDER FORCED DRAUGHT.
TIME
12m
1
2
3
4
5
6
7
8
9
10
11
12
1a.m.
2
3
4
5
6
7
8
9
10
11
12
PERCENTAGE
1
2
3
4
5
6
7
8
9
10

FIG. 1

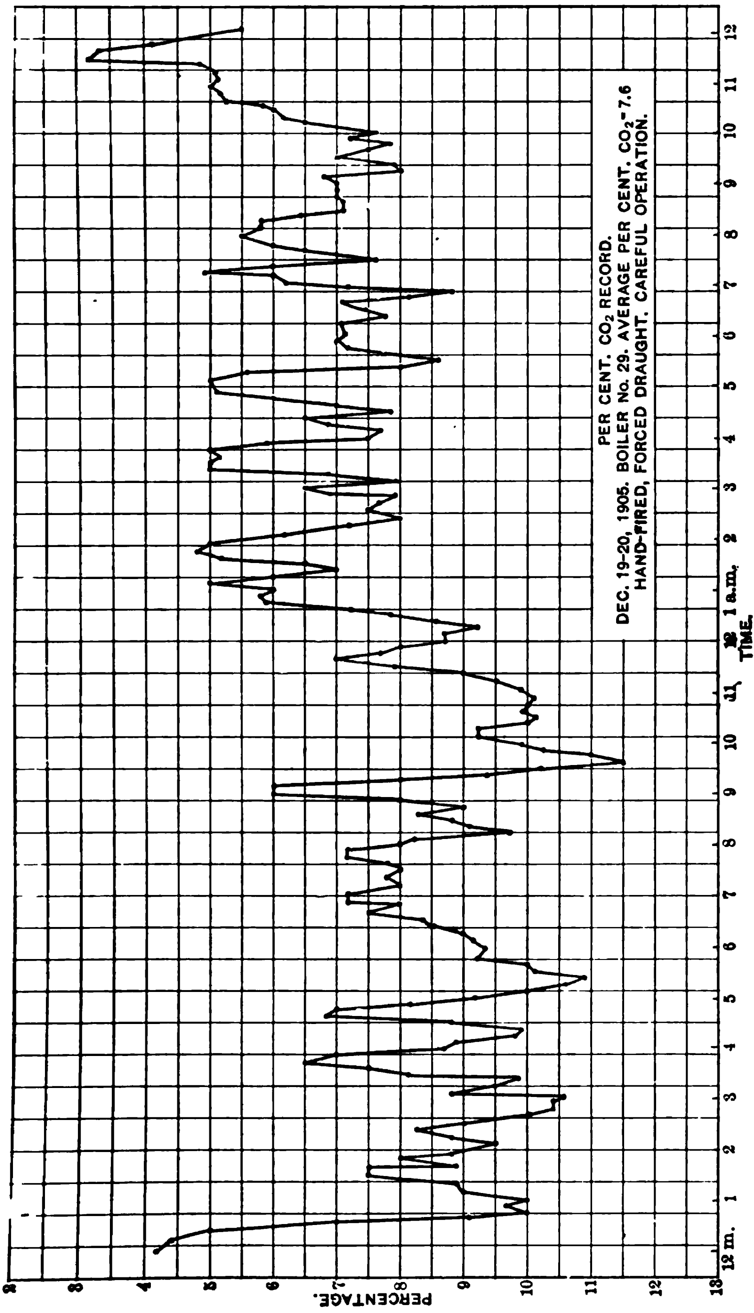
PER CENT. CO_2 RECORD.
DEC. 19-20, 1905. BOILER No. 29. AVERAGE PER CENT. CO_2=7.6
HAND-FIRED, FORCED DRAUGHT. CAREFUL OPERATION.
PERCENTAGE.
2
3
4
5
6
7
8
9
10
11
12
13
TIME.
12 m.
1
2
3
4
5
6
7
8
9
10
11
12
1 a.m.
2
3
4
5
6
7
8
9
10
11
12

FIG. 2.

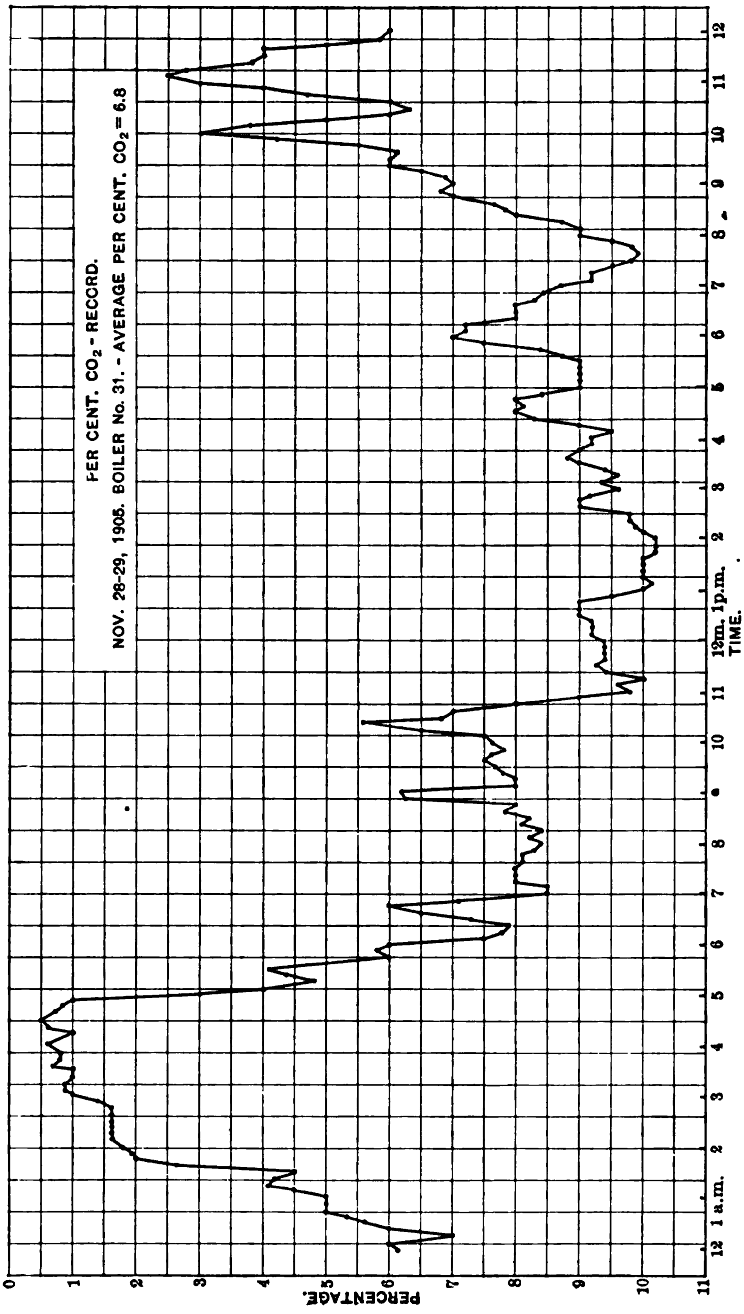
PER CENT. CO₂ - RECORD.
NOV. 28-29, 1905. BOILER No. 31. - AVERAGE PER CENT. CO₂ = 6.8
PERCENTAGE.
0
1
2
3
4
5
6
7
8
9
10
11
TIME.
12
1 a.m.
2
3
4
5
6
7
8
9
10
11
12m.
1p.m.
2
3
4
5
6
7
8
9
10
11
12

FIG. 3

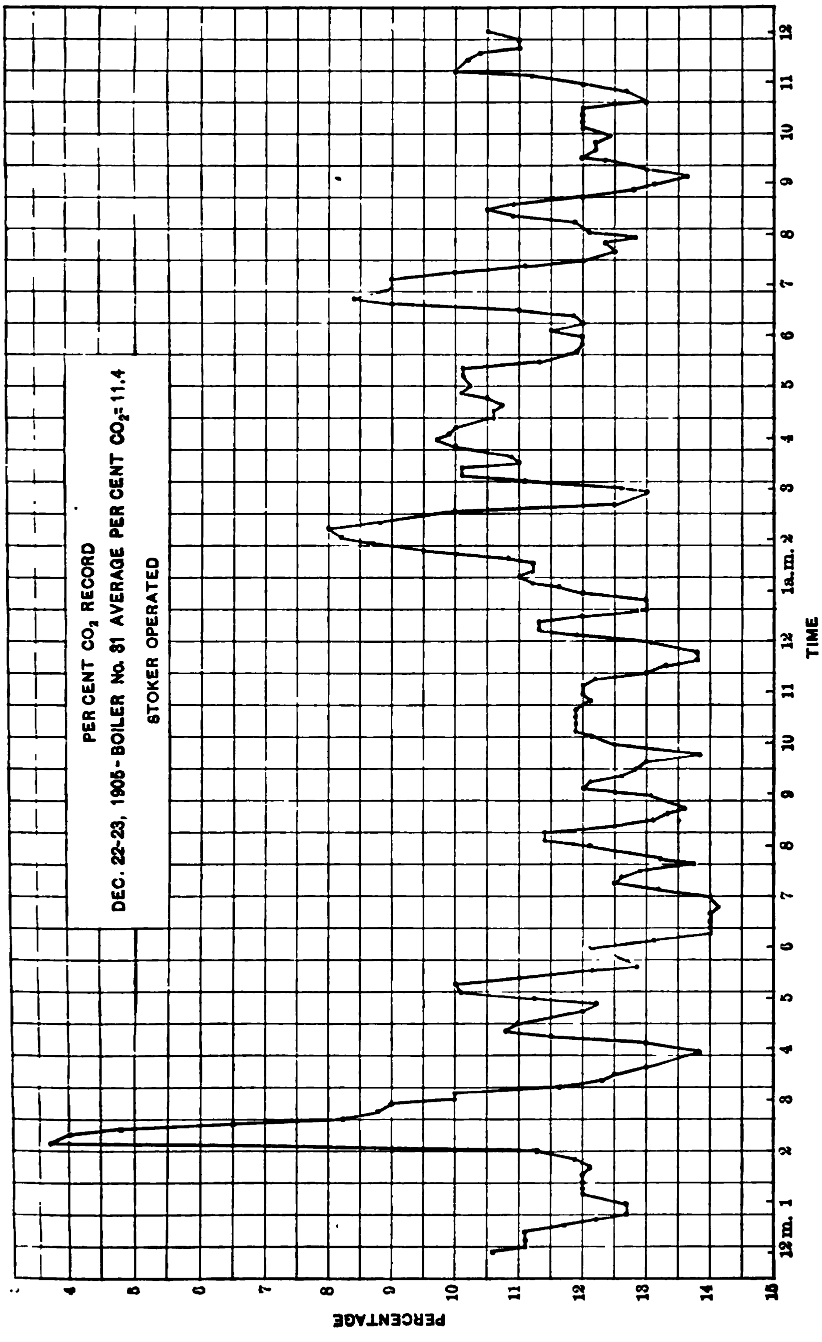
PER CENT CO₂ RECORD
DEC. 22-23, 1905 - BOILER No. 31 AVERAGE PER CENT CO₂ = 11.4
STOKER OPERATED
PERCENTAGE
4
5
6
7
8
9
10
11
12
13
14
15
TIME
12 m.
1
2
3
4
5
6
7
8
9
10
11
12
1a.m.
2
3
4
5
6
7
8
9
10
11
12

Fig. 4.

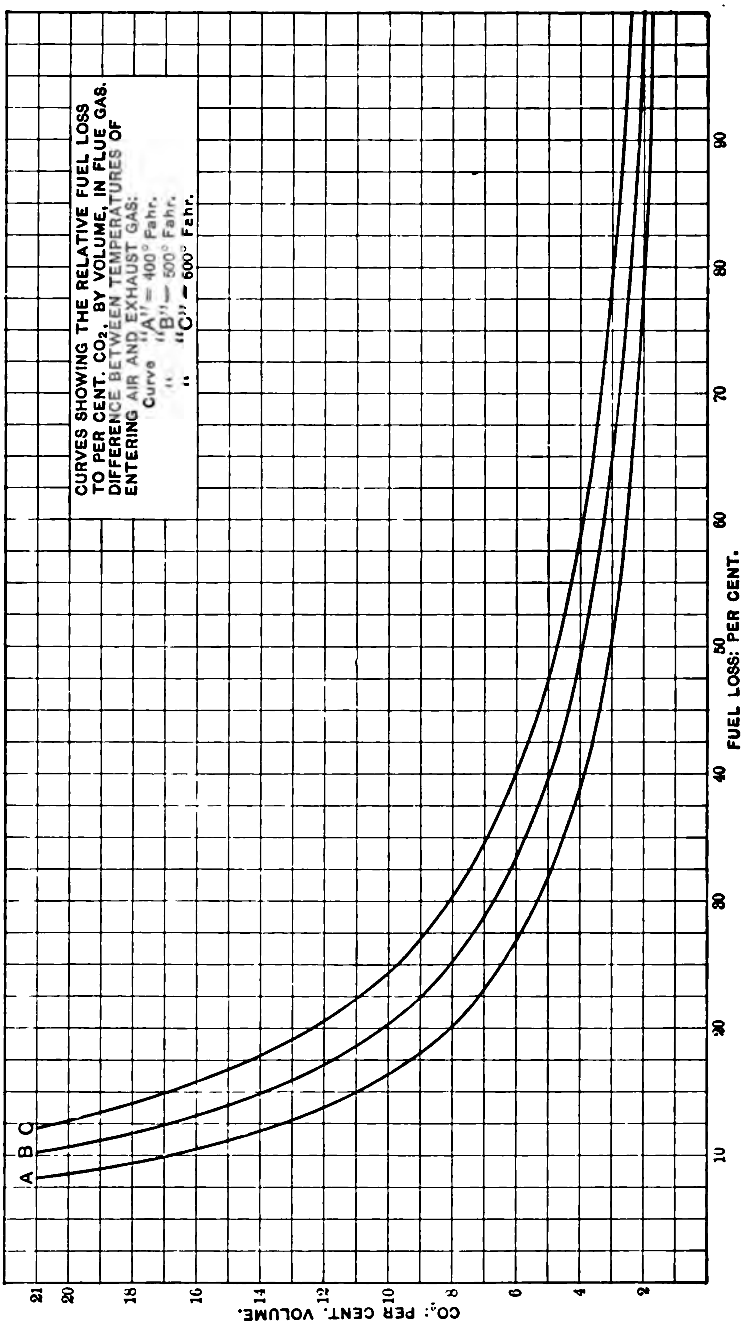
CURVES SHOWING THE RELATIVE FUEL LOSS
TO PER CENT. CO₂, BY VOLUME, IN FLUE GAS.
DIFFERENCE BETWEEN TEMPERATURES OF
ENTERING AIR AND EXHAUST GAS:
Curve "A" = 400° Fahr.
" "B" = 500° Fahr.
" "C" = 600° Fahr.
A
B
C
21
20
18
16
14
12
10
8
6
4
2
CO₂: PER CENT. VOLUME.
10
20
30
40
50
60
70
80
90
FUEL LOSS: PER CENT.

Fig. 5.

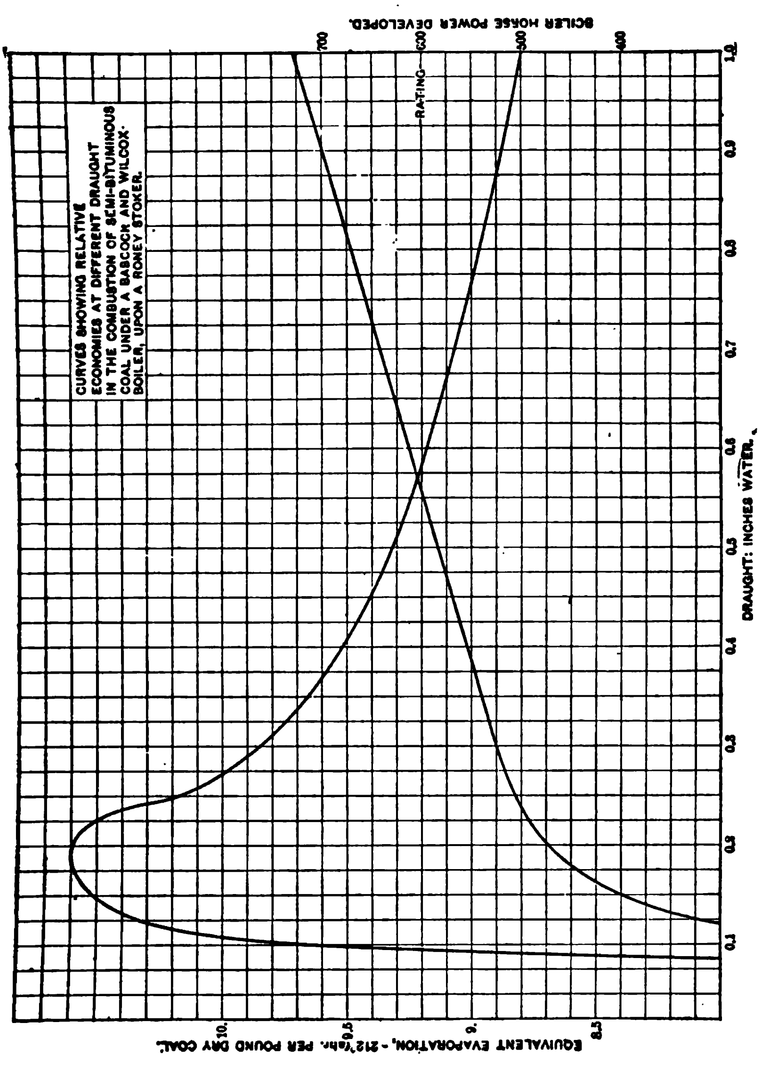
CURVES SHOWING RELATIVE ECONOMIES AT DIFFERENT DRAUGHT IN THE COMBUSTION OF SEMI-BITUMINOUS COAL UNDER A BABCOCK AND WILCOX BOILER, UPON A RONEY STOKER.
BOILER HORSE POWER DEVELOPED.
700
600
500
400
RATING
EQUIVALENT EVAPORATION, - 212°fahr. PER POUND DRY COAL.
10.
9.5
9.
8.5
DRAUGHT: INCHES WATER.
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIG. 6.

Item 3. *Loss to Stack.* This is one of the most vulnerable points to attack, as the loss of 22.7 per cent. is very large. Recent investigations show that promising results may be obtained by the use of more scientific methods in the boiler room.

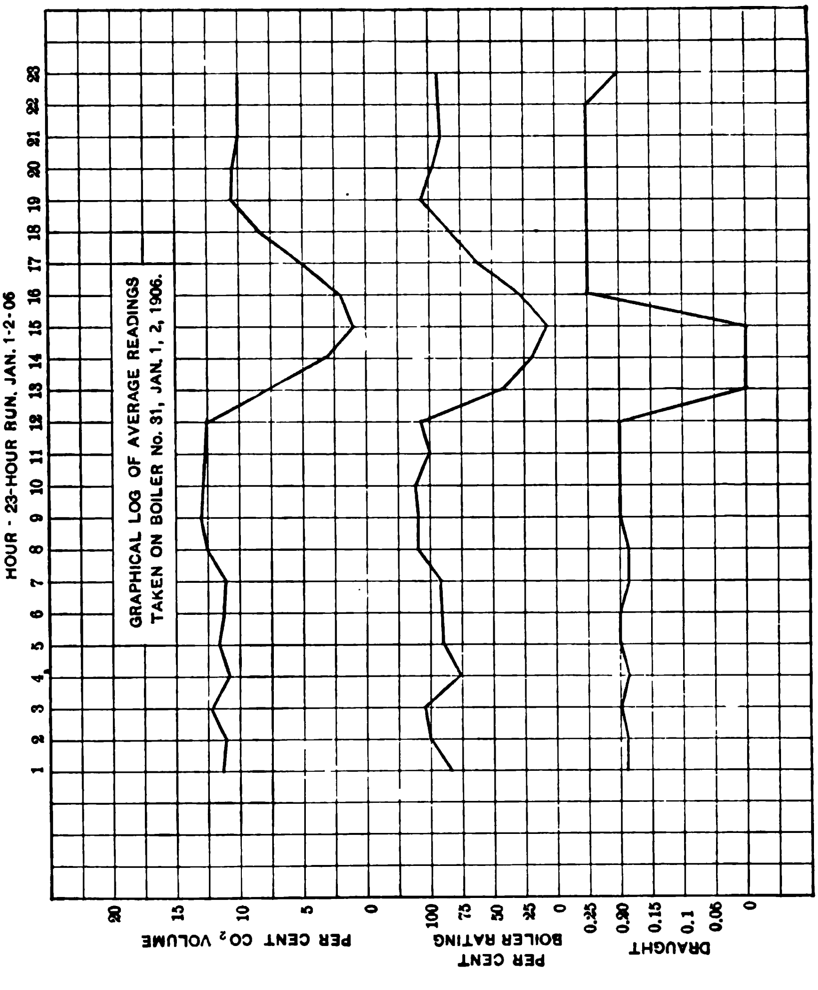

Fig. 7.

In practically all cases it will be found that this loss is due almost entirely to admitting too much air to the combustion chamber, resulting in cooling of the furnace. This result is usually produced by " holes " in the fire; these " holes " may be due to several causes, but usually are due to carelessness on the part of the fireman.

Fortunately, a very valuable piece of apparatus has been placed upon the market in the shape of a CO_2 recording instrument. The results of a series of tests made with this instrument are shown in Figs. 1 to 4.

Fig. 1 shows the average condition of a furnace using small sizes of anthracite, with forced draught. The conditions are such that approximately 40 per cent, of the thermal value is being lost.

Fig. 2 shows what improvement may easily be obtained by watching the CO_2 record, and indicates a saving of about 19 per cent. over the previous case.

In the combustion of the small sizes of anthracite it is necessary to use a draught of not less than 1.5 in. of water; this breaks the crust of the fire in the thin spots, allowing the air to come through in such volumes that an enormous amount of heat is wasted in raising the temperature of the surplus air and at the same time causing inefficient combustion in the entire furnace.

Fig. 3 shows a record taken from a stoker boiler whilst the recorder was covered up to prevent the fireman from seeing the record.

Fig. 4 shows a record taken from the same stoker boiler with the fireman watching the CO_2 indications, resulting in a saving of over 12 per cent. Later records show that even better results than an average of 11.4 per cent. of CO_2 can be obtained.

Fig. 5 shows the calculated losses in fuel corresponding to various percentages of CO_2 for three different temperatures of flue gases.

From a consideration of the above tests it seems reasonable to assume that the 22.7 per cent. loss to stack can, by scientific methods in the fire room, be reduced to about 12.7 per cent. and possibly to 10 per cent.

Before the installation of the CO_2 recorder a long series of evaporative tests was made to determine the most economical draught to carry when a high-grade semi-bituminous coal was burning on the automatic stokers. The results shown in Fig. 6 were so remarkable that they were repeated under different conditions in order to confirm them. Since the installation of the CO_2 recorder, however, the explanation is apparent· as the draught giving maximum evaporation per pound of combustible corresponds to the point of maximum CO_2, illustrating the inherent difficulty of maintaining efficient conditions in the combustion chamber with high draught. This is well illustrated by Fig. 7, showing the draught, per cent. of rating, and percentage of CO_2.

Item 4. The loss in boiler radiation and leakage, amounting to eight per cent., is largely due to the inefficient boiler setting of brick which, besides permitting radiation, admits a large amount of air by infiltration. This infiltration will increase with the draught, thus tending to exaggerate the maximum and minimum points on Fig. 6. The remedy for this radiation and infiltration loss is evidently to use new methods of boiler setting, such as an iron plate air-tight case enclosing a carbonate of magnesia lining outside the brickwork.

Mr. W. H. Patchell,* of London, who recently visited us, has introduced very large boilers, assembling two in one setting; each boiler has a normal evaporation of 33 000 lb. per hour and in this way has cut down to a minimum the radiating surface per square foot of heating surface. He has also introduced the iron case with magnesia lining, and with good results.

The question of boiler leakage is one in which the choice of the lesser of two evils is necessary; for in the tubular or cylindrical boiler the leakage will undoubtedly be less than in the water-tube type, owing to the smaller number of joints in the water space. But these two advantages are offset by the increased difficulty of construction, and the danger of using large boilers of the tubular type, especially with high-pressure steam.

It is now generally admitted that there can be no more difference in the efficiency of different types of boilers under similar conditions than there can be in electric heaters, press agents to the contrary notwithstanding.

Item 5. *Returned by Feed-Water Heater.* The importance of getting the feed water to the maximum temperature obtainable is generally recognized, and would seem to indicate that all auxiliaries should be steam driven so that their exhaust may be utilized in the feed-water heater; in this way the auxiliaries may operate at about 80 per cent. thermal efficiency.

Item 6. Owing to the difficulty of pumping water at tem-

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* See paper read Dec. 7, 1905, before the Institution of Electrical Engineers, by W. H. Patchell.

peratures above 150 degrees fahr., when under pressure, it becomes necessary to install economizers for the purpose of increasing the feed-water temperature to 200 or 250 degrees fahr. As this increase of temperature is obtained from the waste gases at no expense for fuel, it only becomes necessary to consider the load-factor, as will be shown later, in order to decide whether economizers should be installed or not. In practically all cases where the load factor exceeds 25 per cent. the investment will be justified.

In deciding upon the size of economizer to be installed it is important to consider first, the influence of the economizer upon the available draught due to the obstruction it offers and also due to the reduced stack temperature; the second important consideration is to equate the interest and depreciation charges against the saving in fuel, and so determine the amount of investment justified in each particular case.

Item 7. *Loss in Pipe Radiation.* By the use of two-layer pipe covering, each layer being approximately 1.5-in. thick, and sections put on in such manner that all joints are broken, the radiation losses have become practically negligible.

Items 8 and 9. *Heat Delivered to Circulating and Boiler-Feed Pumps.* As these auxiliaries may be either electrically driven or steam driven it is interesting to note that the thermal efficiency of the electrically-driven pumps would be equal to the thermal efficiency of the plant, multiplied by both the efficiency of conversion from the alternating to direct current and by the motor efficiency. In this case, there would be a net thermal efficiency of $10.3 \times 0.93 \times 0.90 = 8.63$ per cent., whereas the thermal efficiency of the steam-driven auxiliary discharging its exhaust into a feed-water heater at atmospheric pressure would be approximately 87 per cent.

Item 10. *Loss in Leakage and High-Pressure Drips.* The loss in leakage should be infinitesimal, and the high-pressure drips can be returned to the boilers, so that practically all the loss under this heading is recoverable.

Items 11, 12, *and* 17 are probably unavoidable and of so small a magnitude as not to merit much consideration.

Item 13. *Loss in Engine Friction.* Recent tests of a 7 500-h.p. reciprocating engine show a mechanical efficiency of 93.65 per cent. at full load, or an engine friction of 6.35 per cent. As this forms only 0.8 per cent. of the total thermal losses it is relatively unimportant. Attention is called to the method of lubricating all the principal bearings by what is known as the flushing system, whereby a large quantity of oil is put through all the bearings by gravity feed from elevated oil reservoirs common to all the units; after passing through the bearings the oil is returned by gravity to oil filters in the basement and then pumped up to the reservoir tanks again. About 200 gallons per hour are put through each engine, and of this quantity only about 0.5 per cent. is lost. This method of oiling undoubtedly contributes to the general result.

Item 14. As large electrical generators can now be obtained which give from 98 to 98.5 per cent. efficiency, it would seem as if the limit in design had been reached and that hereafter the problem of design is to be merely one of altering dimensions to suit varying sizes and speeds. While this is true as far as the efficiency is concerned, other problems are continually arising, such as the design of generators for an overload capacity of 100 per cent. to meet the demand for apparatus capable of taking care of great overloads economically for short periods, corresponding to peak loads of a railroad or lighting plant.

Item 15. *Engine Radiation Losses.* This source of loss has evidently been reduced to a negligible quantity by the use of improved material and methods of heat insulation.

Item 16. *Rejected to Condenser,* 60.1 *per cent.* This immediately introduces the thermodynamics of the steam engine, a subject so broad that it will be impossible to do more than touch upon some of the most important points in considering steam-engine efficiency.

The efficiency of any heat engine can be expressed by the ratio of $E = \frac{T_1 - T_2}{T_1}$ where T_1 is the absolute temperature of the steam entering the engine and T_2 the absolute temperature of the steam leaving the engine. Thus in the engine whose steam-consumption curve is given in Fig. 8, if the initial pressure is 175 lb. gauge and the vacuum at the low-pressure exhaust nozzle is 28 in., then the maximum thermal efficiency is $\frac{837 - 560}{837} = 33$ per cent. This would be true for any form of engine or turbine working between the same temperature limits.

In Fig. 8, however, it is seen that the point of maximum economy shows a steam consumption of approximately 17 lb.

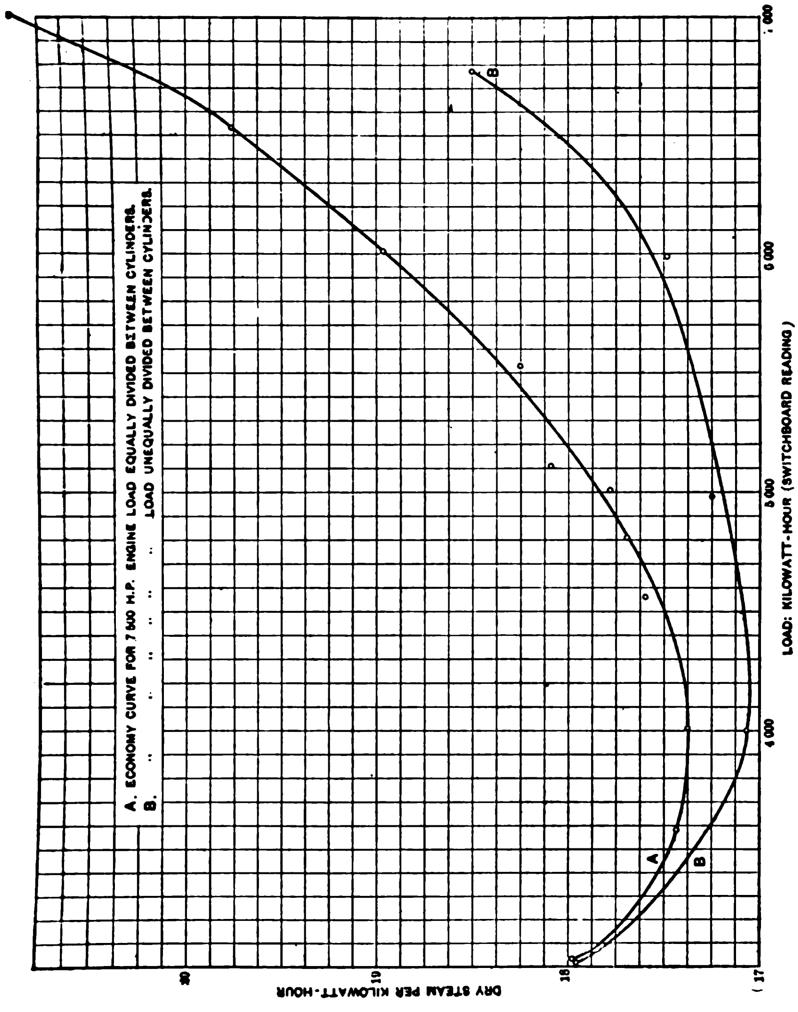
A. ECONOMY CURVE FOR 7 500 H.P. ENGINE LOAD EQUALLY DIVIDED BETWEEN CYLINDERS.
B. " " " " " LOAD UNEQUALLY DIVIDED BETWEEN CYLINDERS.
A
B
A
B
17
18
19
20
DRY STEAM PER KILOWATT-HOUR
4 000
5 000
6 000
7 000
LOAD: KILOWATT-HOUR (SWITCHBOARD READING)

FIG 8

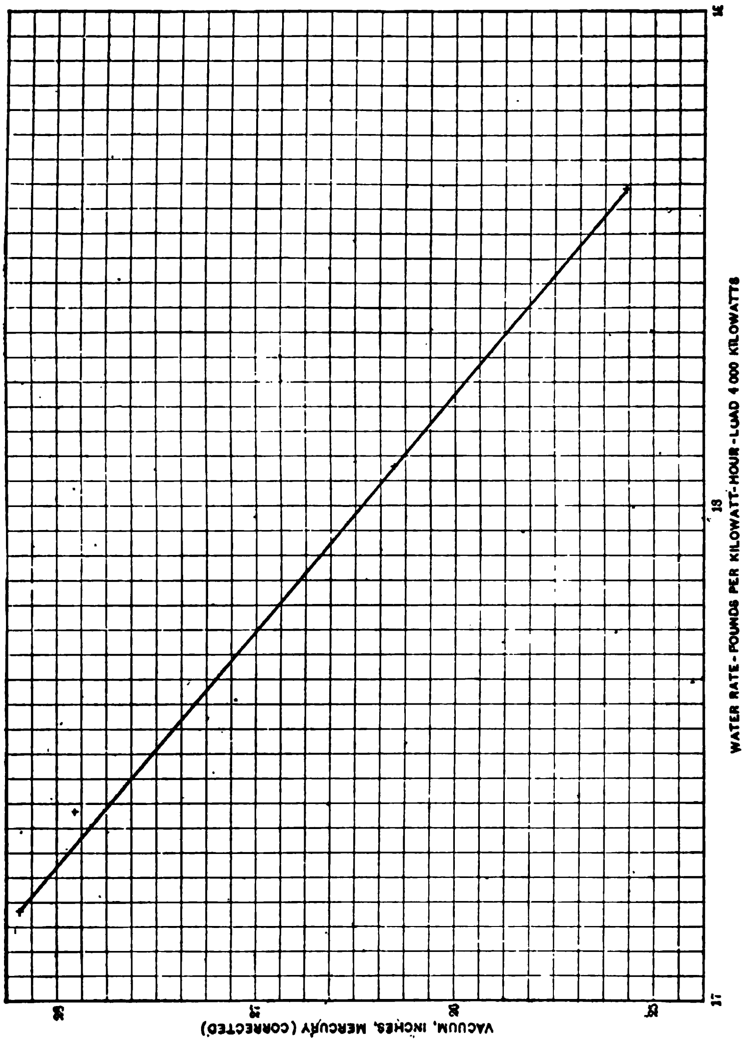
WATER RATE - POUNDS PER KILOWATT-HOUR - LOAD 4 000 KILOWATTS
17
18
19
VACUUM, INCHES, MERCURY (CORRECTED)
29
28
27
26

Fig. 9.

per kilowatt-hour, which is equivalent to 20 349 B.t.u. per hour. One kilowatt-hour is equal to 3 412 B.t.u. per hour, so that the actual efficiency of the steam engine and generator is $= \frac{3\,412}{20\,349} = 16.7$ per cent. As the generator efficiency at this load is approximately 98 per cent. the net engine thermodynamic efficiency is $\frac{16.7}{0.98} = 17$ per cent.

The difference between the theoretical efficiency and the actual is then $33 - 17 = 16$ per cent., of which 0.8 per cent. has already been accounted for in engine friction, so that the balance of 15.2 per cent. is due to cylinder condensation, incomplete expansion, and radiation.

As the engine friction in a two-bearing engine with high-pressure poppet valves and low-pressure Corliss valves has by careful design been reduced to less than 0.8 per cent. gain can not be expected here, so attention must be centered on the loss due to cylinder condensation, etc., amounting to 15.2 per cent., in order to effect any improvement.

Superheated steam is the only remedy at hand and with it we can probably effect an improvement of 5 or 6 per cent. by using such a degree of superheat in the boilers that dry steam will be had at the point of cut-off in the low-pressure cylinder.

Any greater amount of superheat than this will merely result in loss to the condenser; for it should be remembered that the cylinder losses increase with the difference in temperature between the steam and exhaust portions of the cycle; in other words, the greater the thermal range of temperature the greater the condensation loss. This would seem to point to the use of more cylinders; but this involves additional first cost and friction as well as more space and higher maintenance charges.

Fig. 9 shows what may be gained by reducing the temperature at the end of the cycle by means of increased vacuum, but in the case in point the maximum vacuum obtainable in practice was used so that no additional economy can be expected in this way.

SUMMARY OF ANALYSIS OF HEAT BALANCE.

The present type of power plant using reciprocating engines can be improved in efficiency as follows:

Reduction of stack losses......................12%

Reduction in boiler radiation and leakage....... 5%

Reduction in engine losses by the use of superheat. 6%

resulting in a net increase of thermal efficiency of the entire plant of 4.14 per cent., and bringing up the total thermal efficiency from 10.3 per cent. to 14.44 per cent.

THE STEAM TURBINE.

A typical economy curve of a steam turbine is shown in Fig. 10. An inspection of this curve, which represents what is probably the best results obtained up to date, shows: first, that the best economy on dry saturated steam is practically equal to that of the reciprocating engine in Fig. 8; secondly, that 200 degrees superheat reduces the steam consumption 13.5 per cent. But calculating the total heat units in superheat from $H_1 = H + 0.48\ (t_2 - t_1)$ the B.t.u. per kilowatt-hour are 20 349 for dry saturated steam, whilst for 200 degrees superheat they are 19 008 or a net thermal saving of 6.6 per cent. The shape of the economy curve, however, is much flatter than that of the reciprocating engine, so that the all-day efficiency of the turbo unit would be considerably better than that of the reciprocating engine, with the other great advantage of costing approximately 33 per cent. less for the combined steam motor and electric generator.

HIGH-PRESSURE RECIPROCATING ENGINE WITH LOW-PRESSURE TURBINE ON ITS EXHAUST.

The inherent principles involved in the design of the steam turbine show that it can be expected to give an almost perfect adiabatic expansion, as there are no thermal cycles of heating and cooling at every stroke as in the reciprocating engine; there is an almost ideal thermal drop from the steam valve to the condenser. It is also evident that the expansion will be relatively more nearly adiabatic in the low-pressure stage of the turbine than in the low-pressure cylinder of the engine, so that it has been proposed that the reciprocating engine should be run high pressure where relatively it is more efficient than the steam turbine, utilizing the turbine for the low-pressure part of the cycle. In other words, use each where it is most efficient.

The following calculations show approximately what might be expected from such a combination.

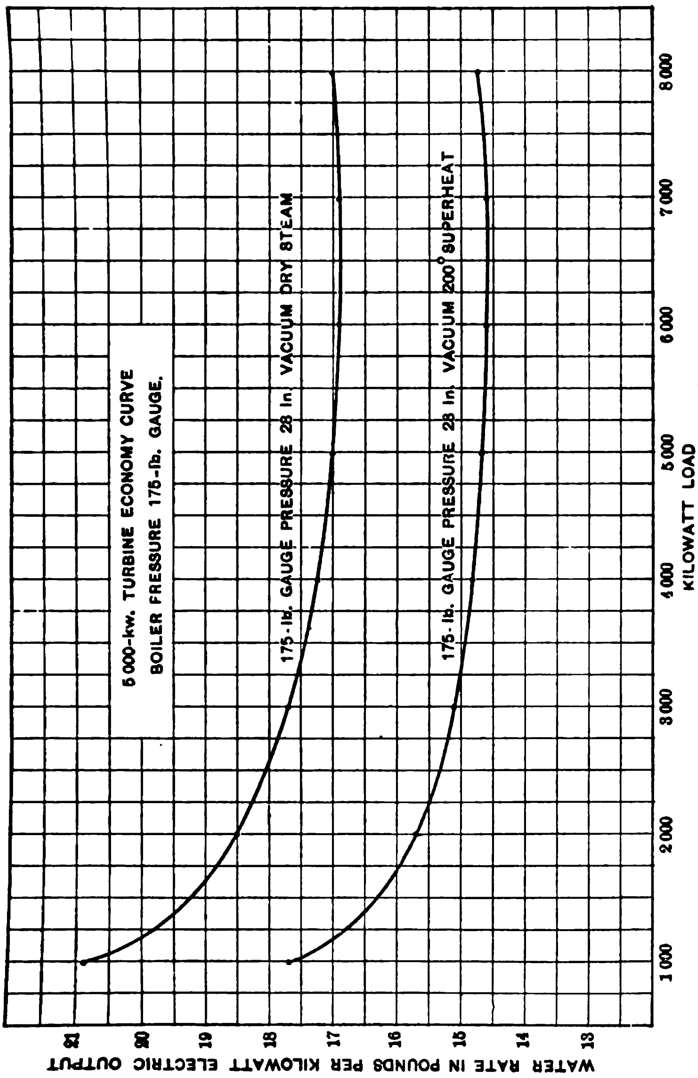
5 000-kw. TURBINE ECONOMY CURVE
BOILER PRESSURE 175-lb. GAUGE.
175-lb. GAUGE PRESSURE 28 In. VACUUM DRY STEAM
175-lb. GAUGE PRESSURE 28 In. VACUUM 200° SUPERHEAT
1000
2000
3000
4000
5000
6000
7000
8000
KILOWATT LOAD
21
20
19
18
17
16
15
14
13
WATER RATE IN POUNDS PER KILOWATT ELECTRIC OUTPUT

Fig. 10

The 5 000-kw. reciprocating-engine unit whose economy curve is shown in Fig. 8 was tested running non-condensing and found to take 25.5 lb. of steam per kilowatt-hour, or 50 % more steam than when running condensing.

This unit would then deliver 127 500 lb. of steam to a specially designed low-pressure turbine. By the use of superheat in the main steam supply, steam having a quality of at least 90 % could be delivered to the turbine, and recent experiments indicate that this low pressure turbine could be expected to develop a kilowatt-hour on 26.5 lb. (This figure can evidently be greatly improved by the introduction of superheat into the low-pressure exhaust steam from the engine).

The total power developed from the combined unit would then be 5 000 kw. + 4 807 kw. = 9 807 kw. at a total expenditure of 127 500 lb. of steam per hour, or of 13 lb. steam per kilowatt-hour for the combined unit.

This turbo unit would be interposed directly between the exhaust nozzle of the reciprocating engine and the condenser, and would have no valves or governing mechanism whatever. The generator would be connected directly to the other generator leads without any switching apparatus, except possibly knife switches to disconnect for testing purposes; and in operation no attention whatever would be required beyond the ordinary lubrication of bearings. Such a unit it is evident could be built at a very small cost per kilowatt-hour.

THE INTERNAL COMBUSTION OR GAS ENGINE.

The gas engine has probably developed more slowly than any other piece of modern apparatus, as it is now thirty years since the Otto gas engine was introduced. It is only within the last ten years that the larger type of engine, from 500 to 2 000 h.p. in size, has appeared. The delay in bringing forward the most efficient motive power known is chiefly due to the difficulty experienced in developing an efficient and inexpensive method of making gas. As far as the production of gas from anthracite and non-caking bituminous coals is concerned this problem has apparently been solved, but it is still in a more or less unsolved condition for the richer bituminous and semi-bituminous caking coals of the eastern states.

The following heat balance is believed to represent the best results obtained in Europe and the United States up to date in the formation and utilization of producer gas.

ANALYSIS OF THE AVERAGE LOSSES IN THE CONVERSION OF ONE POUND OF COAL CONTAINING 12 500 B.T.U. INTO ELECTRICITY.

	B.t.u.	Per cent.
1. Loss in gas producer and auxiliaries	2 500	20.
2. Loss in cooling water in jackets	2 375	19.
3. Loss in exhaust gases	3 750	30.
4. Loss in engine friction	813	6.5
5. Loss in electric generator	62	0.5
6. Total losses	9 500	76.0
7. Converted into electrical energy	3 000	24.0
	12 500	100.0

The great objection to the use of the gas engine for electrical purposes has been: first, its lack of uniform angular velocity; secondly, its uncertainty in action and high cost of maintenance; and thirdly, its inability to carry heavy overloads. Recent developments have removed the first and second objections; and a period of vigorous development has resulted in placing the gas engine in the front rank of claimants for attention as a prime mover.

The total investment for a gas-producer plant, all auxiliaries, gas engines, and electric generators, has been reduced by the elimination of the gas-holding tank to a point where it is now practically on a par with a first-class steam plant using high-grade reciprocating engines.

Where natural gas or blast-furnace gas can be obtained the gas engine has outdistanced all competitors; and now that some of our large manufacturers have taken up in earnest the problem of designing producer-gas plants, it is safe to say that rapid developments will result.

The records of operation of several important installations of gas engines in power plants abroad and in this country seem to indicate that only one important objection can be raised to this prime mover, and that is that its range of economical load is practically limited to between 50 per cent. load and full load, as shown in Fig. 11. This lack of overload capacity is probably a fatal defect for the ordinary power plant, more especially for the average railroad plant operating under a violently fluctuating load, unless protected by a storage-battery of comparatively large capacity.

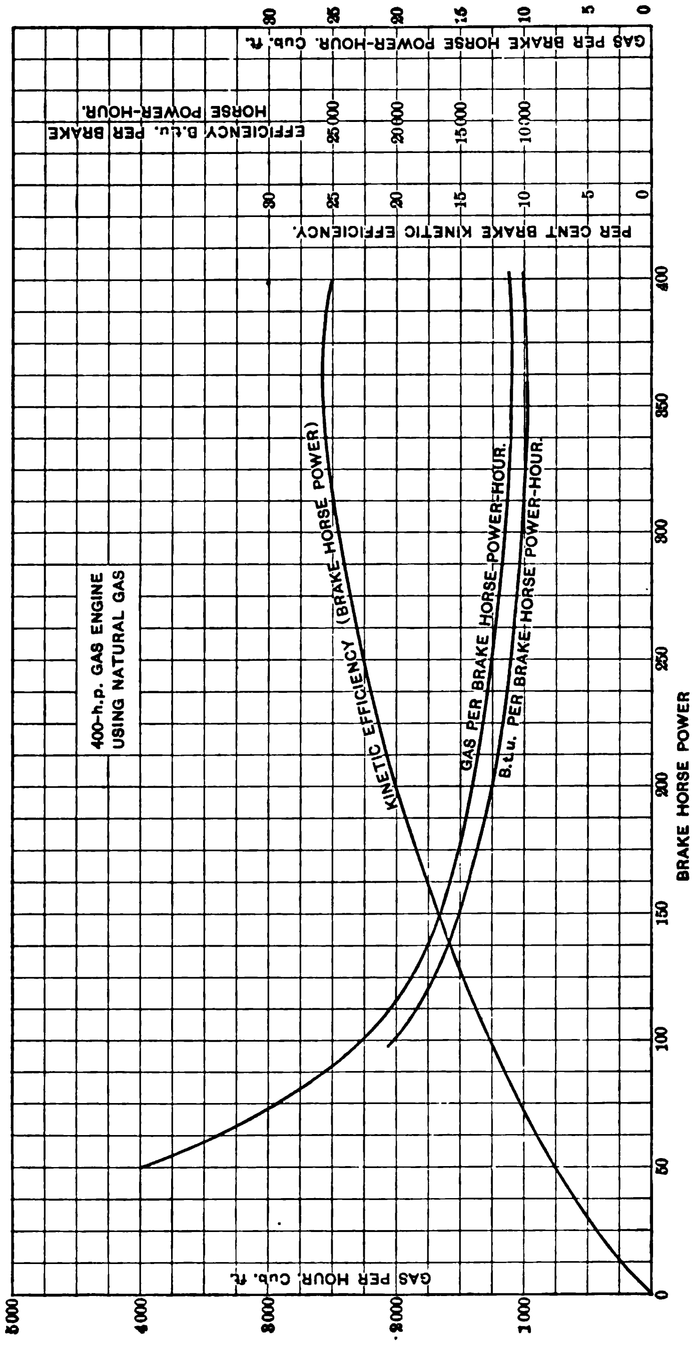
GAS PER BRAKE HORSE POWER-HOUR. Cub. ft.
30
25
20
15
10
5
0
EFFICIENCY B.t.u. PER BRAKE HORSE POWER-HOUR.
25000
20000
15000
10000
PER CENT BRAKE KINETIC EFFICIENCY.
30
25
20
15
10
5
0
400-h.p. GAS ENGINE
USING NATURAL GAS
KINETIC EFFICIENCY (BRAKE-HORSE POWER)
GAS PER BRAKE HORSE-POWER-HOUR.
B.t.u. PER BRAKE-HORSE POWER-HOUR.
GAS PER HOUR, Cub. ft.
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
350
400
BRAKE HORSE POWER

FIG. 11.

NEW TYPE OF PLANT.

Over a year ago, while watching the effect of putting a large steam turbine having a sensitive governor in multiple with reciprocating engine-driven units having sluggish governors, it occurred to the author that here was the solution of the gas-engine problem; for the turbine immediately proceeded to act like an ideal storage-battery; that is, a storage-battery whose potential will not fall at the moment of taking up load, for all the load fluctuations of the plant were taken up by the steam turbine, and the reciprocating units went on carrying almost constant load, whilst the turbine load fluctuated between 0 and 8 000 kw. in periods of less than 10 seconds.

The combination of gas engines and steam turbines in a single plant offers possibilities of improved efficiency whilst at the same time removing the only valid objection to the gas engine.

A steam-turbine unit can easily be designed to take care of 100 per cent. overload for a few seconds; and as the load fluctuations in any plant will probably not average more than 25%, with a maximum of 50% for a few seconds, it would seem that if a plant were designed to operate normally with 50% of its capacity in gas engines and 50% in steam turbines, any fluctuations of load likely to arise in practice could be taken care of.

We have seen that the thermal losses in the gas-engine jacket-water amounted to approximately 19%, and as the water is discharged at a temperature above 100° it can be used to advantage for boiler feed.

The jacket-water necessary for an internal combustion engine will probably be about 40 lb. per kilowatt-hour, assuming that the jacket-water enters at 50° fahr.; then the discharge temperature will be $50+\frac{19\times 12\,500}{40\times 100} = 109.4°$ fahr.

As the steam turbine will require only about 15 lb. per kilowatt-hour, including auxiliaries, it is evident that only 37.5% of this heat or 7.1% of the jacket-water loss can be utilized. The other loss in the exhaust gases of 30% can be utilized either in economizers or directly in boilers or superheaters.

Thus by utilizing the waste heat in the gas engines for the purpose of assisting to make steam for the turbines, there can be saved approximately 37% of the total heat lost in the gas engine.

In the summary of analysis of heat balance it was shown that one can reasonably expect to bring the reciprocating engine plant up to a maximum total thermal efficiency of 14.44%, or possibly with steam turbines using superheat, to 15%.

Referring now to Table 1 it will be noted that in Item 2 the loss in ashes was 2.4%, and the loss to stack in Item 3 was 22.7%; now with the hot gases from the gas-engine exhaust it is evident that the loss in 2 will not exist, and that Item 3 will be reduced from 22.7% to about 5% as the process of combustion is completed in the gas engine. The total efficiency of conversion of this 30% of heat from the waste gases when used in the turbine plant would then be $15.0+2.4+(22.7-5)=35.1\%$.

The heat recoverable from the jacket-water was shown to be 7.1% of the total heat in the coal so that there is $30\%+7.1\%=37.1\%$ of the original heat in the fuel returned from the gas engine, and this can be converted into electrical energy at an efficiency of 35.1%.

For each kilowatt delivered by the gas-engine plant, 3 918 B.t.u. will be simultaneously turned over to the steam plant, and this in turn will give 403 watts to the steam plant free of cost.

The steam plant will then have only to furnish $1\,000-403$, or 597 watts per kilowatt at a thermal efficiency of 15%; in other words, the economy of the steam part of the plant will be raised to $\frac{15}{0.597}=25\%$.

The average total thermal efficiency of such a combination plant would then be $\frac{24+25}{2}=24.5\%$.

LOAD-FACTOR AND INVESTMENT.

In Fig. 12 the interest depreciation and taxes on a plant costing $130.00 per kilowatt, which may be taken to represent a first-class steam or internal combustion plant, is shown plotted in conjunction with various load-factors.

Another curve is plotted showing the minimum investment with a plant in which the prime mover would be steam turbines and designed otherwise without regard to efficiency, leaving out economizers, feed-water heaters, etc., and thus reducing the investment to $90.00 per kilowatt. This cheap and relatively inefficient part of the plant would only be operated on

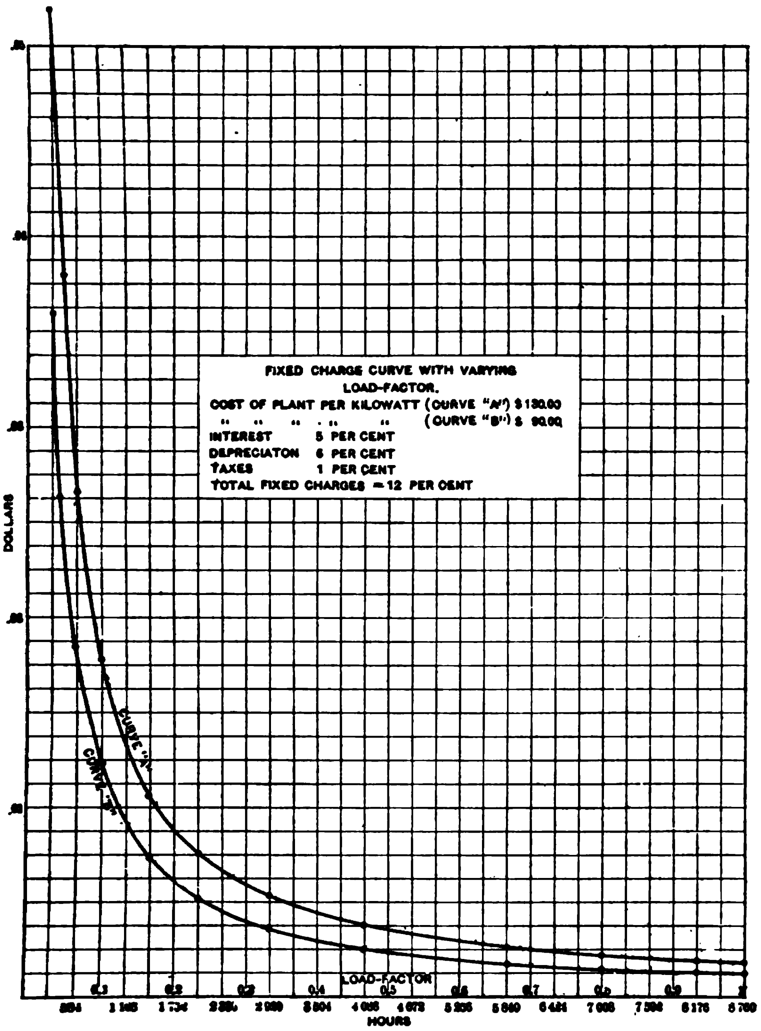
FIXED CHARGE CURVE WITH VARYING
LOAD-FACTOR.
COST OF PLANT PER KILOWATT (CURVE "A") $130.00
" " " " " (CURVE "B") $ 90.00
INTEREST 5 PER CENT
DEPRECIATON 6 PER CENT
TAXES 1 PER CENT
TOTAL FIXED CHARGES = 12 PER CENT
DOLLARS
CURVE "A"
CURVE "B"
LOAD-FACTOR
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
584
1168
1752
2336
2920
3504
4088
4672
5256
5840
6424
7008
7592
8176
8760
HOURS

FIG. 12.

peak loads of two or three hours' duration, corresponding to a load-factor of 0.1 or less found in possibly 40% of the output of our lighting plants.

In Table 2 will be found a tabulation of the relative values of the various items necessary in the maintenance and operation of a power plant. The first column covers a plant with compound condensing reciprocating engines without superheat, and is derived from a year's record of actual costs of a

TABLE II.

DISTRIBUTION OF MAINTENANCE AND OPERATION. CHARGES PER KILOWATT-HOUR.

	Recip-rocating Engines	Steam Turbines	Recip-rocating Engines & Steam Turbines	Gas-Engine Plant	Gas Engines and Steam Turbines
MAINTENANCE.					
1. Engine room mechanical	2.57	0.51	1.54	2.57	1.54
2. Boiler room or producer room	4.61	4.30	3.52	1.15	1.95
3. Coal- and ash-handling apparatus	0.58	0.54	0.44	0.29	0.29
4. Electrical apparatus	1.12	1.12	1.12	1.12	1.12
OPERATION.					
5. Coal- and ash-handling labor	2.26	2.11	1.74	1.13	1.13
6. Removal of ashes	1.06	0.94	0.80	0.53	0.53
7. Dock rental	0.74	0.74	0.74	0.74	0.74
8. Boiler-room labor	7.15	6.68	5.46	1.79	3.03
9. Boiler-room oil, waste, etc	0.17	0.17	0.17	0.17	0.17
10. Coal	61.30	57.30	46.87	26.31	25.77
11. Water	7.14	0.71	5.46	3.57	2.14
12. Engine-room mechanical labor	6.71	1.35	4.03	6.71	4.03
13. Lubrication	1.77	0.35	1.01	1.77	1.06
14. Waste, etc	0.30	0.30	0.30	0.30	0.30
15. Electrical labor	2.52	2.52	2.52	2.52	2.52
Relative cost of maintenance and operation	100.00	79.64	75.72	50.67	46.32
Relative investment in per cent	100.00	82.50	77.00	100.00	91.20

large plant operating with a load-factor of approximately 50 per cent.; load-factor in this case being defined as

$$\frac{\text{Actual output}}{\text{Maximum hour's load} \times 24}$$

The values in the other columns have in the main been estimated from the first column, but wherever possible actual data derived from various sources, both domestic and foreign, have been used; but in all cases all values have been reduced so as to make them directly comparable with the first column, and with one another. The values in maintenance and operation of steam turbines are derived from actual costs.

SUMMARY.

1. The present type of steam-power plant can be improved in efficiency about 25 per cent. by the use of more scientific methods in the boiler room, by the use of superheat, and by running the present types of reciprocating engines high pressure, and adding a steam turbine in the exhaust between the engine and the condenser. At the same time the output of the plant can be increased to double its present capacity at a comparatively small cost for turbines and boilers.

2. The steam-turbine plant has an inherent economy 20 per cent. better than the best type of reciprocating-engine plant, not so much due to its higher thermal efficiency as to a variety of causes shown in Table 2.

3. An internal combustion-engine plant in combination with a steam-turbine plant offers the most attractive proposition for efficiency and reliability to-day, with the possibility of producing the kilowatt-hour for less than one half its present cost.

DISCUSSION ON "POWER PLANT ECONOMICS," AT NEW YORK. JANUARY 26, 1906.

E. W. Rice, Jr.: In analyzing the losses that take place in the conversion of a pound of coal into electricity in a steam electrical plant, Mr. Stott makes use of the method that has been so successful in increasing the efficiency of electrical apparatus. Twenty years ago efficiencies of 75 or 80 per cent. were considered entirely satisfactory for electrical generators; but by careful attention to the core losses, iron losses, bearing losses, and other details, the efficiency has been increased to 95 or 98.5 per cent. For large units this efficiency is now considered standard. In these matters the electrical engineer has fortunately been greatly aided by the ammeter, voltmeter, and wattmeter, which have been evolved to assist him. Unfortunately, similar instruments do not exist for the examination of steam engines or steam-engine cycles; if the steam engineer had the equivalent of the ammeter and voltmeter, I feel confident that the efficiency of the steam-engine plant would have been very greatly increased.

At this point it is interesting to note the large saving that can be effected in item 3, " Loss to Stack," in Table 1, by intelligently following out the indications given by the CO_2 recorder, a most useful instrument. The author shows quite conclusively the high efficiency of steam auxiliaries. This naturally follows from the fact that the latent heat can be usefully employed to raise the temperature of the feed water. It is evident that in a case where the heat of exhaust can be usefully employed, the mechanical power can be obtained at high efficiency by using steam in a steam engine between boiler pressure and atmospheric exhaust. A familiar illustration of this is to be found in the use of exhaust steam from high-pressure engines to heat buildings. During the period and to the extent that such exhaust steam can be utilized for this purpose, or for manufacturing purposes, mechanical power can be obtained at high efficiency by the use of simple or compound engines operating from boiler pressure down to the pressure of the exhaust. In this case the engine may be considered as a simple reducing valve, reducing the pressure.

From the standpoint of convenience, simplicity, reliability. and avoidance of unnecessary steam pipes, no doubt there is much to be said in favor of electrically-driven auxiliaries, but they cannot compare in heat efficiency with steam-driven auxiliaries. It is unfortunate that no way is known at present of overcoming the losses, some 60 per cent., of heat units rejected to the condenser. This emphasizes the importance of working with the highest possible vacuum. Before the introduction of the steam turbine, there was no demand for a vacuum greater than 26 inches. The steam turbine is so admirably adapted to working over the lower ranges of pressure, that immediately a demand arose for the use of higher vacuum, and it is now common to find vacua of 28.5 to 29 inches the barometer being assumed at 30.

Mr. Stott calls attention to the large increase in output and the improvement of efficiency which results from interposing a turbo electric unit between the exhaust nozzle of the reciprocating engine and the condenser. In Philadelphia there are two 800-kw. turbo generators operating exactly according to the plan proposed by the author of this paper. One of these units has been in operation for the last two months, and the other is, I believe, just started. As a result, there has been added to the power plant a capacity of from 1 600 to 2 000 kw. without any additional consumption of coal or appreciable addition to the labor. If enough turbines were placed in operation in such a plant to utilize all of the exhaust steam, the output could be easily increased by some 66 per cent. The increased investment would possibly be but one-half of the original investment in such a power station.

In view of the higher efficiency of the steam turbine as compared with the reciprocating engine in the lower ranges of pressure, it will be found profitable to employ a steam turbine for even a smaller range of pressure than that between atmosphere and 28.5 inches; in other words, a steam turbine may be inserted in the exhaust between the low-pressure cylinder and the condenser in almost any reciprocating-engine plant. In this case a steam turbine would work over a range of, say, between 20 and 28.5 inches of vacuum, corresponding in absolute pressures to between 10 lb. and 0.75 lb.

I am not quite sure that Mr. Stott recommends the combination of reciprocating engine and steam turbine in the exhaust as something to be considered in planning a new station. If so, it seems to me that the advantages gained by such a combination would not offset the added complexity. I believe, however, it is a most excellent means of increasing the economy, by adding to the output, of existing reciprocating-engine stations. In considering the application of steam turbines to the lower range of pressures, I have found the following table of value:

Number of ft-lb. per lb. of energy in steam between 175 lb. absolute and 0.75 lb. absolute, or 28.5 in. vacuum	262 000
Between 2 lb. absolute, or 26 in. vacuum, and 28.5 in. .	226 600
Between 5 lb. absolute, or 20 in. vacuum, and 28.5 in. .	157 000
Between 14.7 lb. absolute, or atmospheric pressure, and 28.5 in.	139 000

It will be observed from the latter figure that some 53% of the total available energy in steam, between 175 lb. absolute pressure and 28.5 in. vacuum, exists in the so-called vacuum portion, and that some 40% of this energy remains between 20 in. vacuum and 28.5 in. vacuum.

It is also important to remember that if the vacuum can be increased from 28.5 in. to say 29.4 in., the ft. lb. available are increased about 12 per cent.

The author's suggestion of a new type of plant, to obtain the benefits of the gas engine and unite that with the well-known flexibility and overload capacity of the steam turbine, is certainly interesting. The gain in total efficiency is so remarkable as to warrant careful and respectful consideration. I cannot help being surprised at the low estimate of the relative cost of maintenance and operation of a gas-engine plant as compared with the estimates for reciprocating engines or steam turbines, aside, of course, from the item of coal. I was not aware of the existence of sufficient data of this character to warrant such figures.

A word as to the original investment, in considering the relative investment of a plant consisting of reciprocating engines, whether gas or steam, particularly the steam type, as compared with the rotary engine of the steam-turbine type: I think it pertinent and important to consider that reciprocating engines have been built for many years, that the methods of design and manufacture are familiar, and that the cost of manufacture has, probably, therefore been reduced to a minimum. It is hardly reasonable, therefore, to look for any future material reduction in the price of such reciprocating units. The steam turbine, however, is of a comparatively recent date, and it is reasonable to expect, looking forward five or ten years, that improvements in methods of design or manufacture will result in a very material reduction in cost. Furthermore, I have been informed that the cost of reciprocating engines of large size reaches a minimum at sizes of units even below those which are now used in large stations, and the cost may be expected to increase with any material increase in size. On the other hand, the steam turbine shows no such limitations, as there are now in course of manufacture turbine units of 8 000 or 10 000 kw., nominal rating, capable, of course, of the usual 50 per cent. overload, or even double load momentarily. The original investment becomes a most important factor in the operating cost of a power plant, as interest, depreciation, maintenance, are, other things being equal, substantially proportional to the first cost.

It seems to me that while we cannot ignore any substantial increase in the efficiency of conversion of coal into electricity, the central station designer must in the future, even more than in the past, give due heed to the important questions of simplicity and reliability. The plant should have the highest practicable degree of working efficiency, but it must above all things be reliable. I believe that in simplicity and reliability the steam turbine will outdo all rivals. I cannot help feeling that the modern station has developed into a very complicated makeup. I would like to see the units reduced to the fewest practicable number, not only the generating units, but the boilers, auxiliaries, steam pipes, switchboard appliances, etc. The safety devices and instruments should be as simple and as few in number and variety as is consistent with reliable operation of the station.

Charles E. Lucke: I think that the author of this paper has evidently sought to find a place for the reciprocating engine, the steam turbine, and the gas engine. His main conclusion is, that for economy of power generation in cost per kilowatt-hour, including manufactured cost, with interest, depreciation, and other establishment charges, the gas-engine plant offers, in the present type of steam-power plant, much greater economy, twice as much, in fact, as the reciprocating-engine plant; and that with the combination of a turbo-generator and a gas-engine generator. there are still greater economical advantages. In this connection it is necessary to remark that of all the power used throughout the United States, the number of horse power generated in high-efficiency central stations is but a very small percentage. The arguments which apply to stations similar to the station indirectly referred to by the author would not necessarily apply to all power stations under all conditions. There are conditions for every installation which will undoubtedly determine its type, and these are very seldom considerations of high economy or thermal efficiency. If exhaust steam is needed in large quantities—in works where evaporating is to be done, or boiling, or washing, or heating of a building—there can be no discussion of power costs, and the power station simply becomes a question of what steam engine units can be bought and kept in repair for the least money. Steam economy is a matter of no consequence in this case. If property is extremely valuable and the current generated can be sold at a good profit, no matter what the price, then undoubtedly turbines must be selected. If there is an enormous quantity of gas available, as in a blast-furnace plant, then everything points to the selection of the gas engine.

The average small power station for electric generation, when operated by steam, has a very much lower thermal efficiency and a very much higher power-cost, than have these large highly refined stations. If, as proved by the author, power-costs by gas are less for the highly refined station, and if, as is the fact, the gas-engine station does not fall off in efficiency, nor rise in power cost as its size decreases, then it must inevitably follow that the small gas-engine plant for electric generation will have a higher relative value than the large one, compared with steam. The author shows by some very excellent curves that the economy or efficiency of the whole plant will vary with the load, and that for a steam plant the variations are probably the largest and most controllable in the boiler room. He also shows that the boiler economy is very much poorer at high, forced loads than under light loads, and that the only way to guard against this is by eternal watchfulness.

Corresponding to the boiler in the steam plant, there is a gas-producer in the gas plant. The gas-producer is much less sensitive to changes in load, resulting in changes in economy, than the boiler plant. This, I think, is a strong point in favor of the gas-producer plant. Again, there is practically no electric station running on a steady load. The load changes are of two kinds: a steadily-rising load from hour to hour during the day, and a correspondingly decreasing load; also a momentary fluctuation, a sudden rise and an equally sudden drop. The hour-to-hour changes are to be handled in a central station by putting on more units, or by taking them off. This means that in the boiler room there must always be a certain number of fires banked or in reserve, or both. Now, it is also true that the same conditions will prevail in the case of a gas-producer plant, but the coal consumed by banked fires or reserve fires in the gas-producer is very much smaller than for the same horse power of steam boilers. This is another point in favor of the producer gas. The ash loss, which is small in any case, becomes almost zero in the case of the gas-producer; because in the producer there is always left a bed of ash in the bottom, so that coal immediately after being burned does not fall through the grate bars as in the case of steam boilers.

The author calls attention to a load economy curve for a gas engine, and draws the conclusion that a gas engine having this curve should not be used at anything less than half load, because its efficiency falls off very much indeed toward no load. The conclusion is entirely justified with respect to the engine that produced this particular curve, but it is not justified with respect to all gas engines. The reason for the economy of a gas engine varying with the load is to be found in the governing mechanism. This results when the governor of the gas engine acts as a throttle on the mixture; in such a case, for the entire suction stroke of the engine the piston must work against the constantly increasing vacuum clear to the end; that is, there will be a loss due to working below the atmospheric line. If the lost work of the engine, as effected by the governor action, is eliminated or reduced to a minimum, the economy load curve will be perfectly flat. The curve presented becomes then not a criticism of the gas-engine economy, with load, but a criticism of that particular type of governor which, I am confident, will disappear in time.

The superior efficiency of the gas-engine plant is acknowledged, but not so often as it should be. The reciprocating engine has been a long time in reaching the efficiency it has today. For years nothing was done to increase the efficiency of gas engines; and it is only within the last five or six years that there has been any marked activity in improving gas engine efficiency, reliability, and regulation.

It is well known that the efficiency of such a unit depends on the compression, and, therefore, other things being equal, the greater the compression before ignition, the greater the increase in efficiency. Theoretically, there is no limit to the compressing; practically there is, but I am confident that some of these practical difficulties will be overcome in time. At the present time mixtures of air and gas are being used in practically correct chemical proportions, and the compression pressure now used is determined by the temperature of ignition of such a mixture. If such a mixture were diluted; that is, if much excess air or neutral gases or internal cooling were used, then this mixture could be compressed very much more without pre-ignition, and a corresponding gain in efficiency would result. This has not been done up to the present time, simply because no one has yet designed a proper proportioning valve for keeping the mixture constant for all conditions, and because no one has yet designed instruments that will indicate at a glance on a dial the proportions of air to gas, the percentage of dilution of mixture, the B.t.u. per cubic foot of gas, the B.t.u. per cubic foot of mixture, the mean effective pressure, and other similar information.

As designed at present the gas engine can never regulate as well as the turbine. There are gas-engine builders who insist that they can do as well in this respect as turbine builders, but the contention is ridiculous. The gas engine can, however, regulate alternators in parallel sufficiently well for most ordinary work, but the turbine can do even better. In Germany, last summer, I found gas engines as high as 4 000 h.p. single units running on dirty gas and on clean gas, on rich gas and on poor gas, and giving perfect satisfaction, chiefly because they were properly designed and properly handled. I found large units in blast-furnace plants, operating 24 hours a day, for eight weeks without a stop or shut-down of any kind, and more than that, doing something which required most positive certainty of operation. These furnaces were absolutely dependent on an air blast running exclusively on gas engines, and, in more than one case, without a single spare unit. Thousands of dollars were involved in the certainty of the blast, and all went right on from year to year. In spite of sensitiveness to proper handling, some gas engines will run under extremely adverse conditions. In one place in this country I have found the gas very imperfectly cleaned, containing a great deal of grit and dirt that was finally carried into the engines in quite large quantities. Grit and dirt in a gas engine cause trouble; they grind out the pistons, interfere with the valves, and clog the governing mechanism. But though all these things happened in this instance, the engines are still running. Recently I took a gas valve out of one of these engines, and scraped off 20 pounds of oil, ore dust, and coke dust. The valve had been in two months. The engine was still running, and doing its work reasonably well. These are little facts which point a great moral.

The gas engine has a maximum load capacity proportional to its piston displacement, and so has the steam engine. The steam engine is ordinarily operated at less than its maximum load, and is, therefore, said to have an overload capacity. The gas engine is said to have no overload capacity, because it is intended normally to operate at nearly its maximum load. Now, if a gas-engine plant were to be handled as the steam plant is, then there would be considerable difficulty about meeting the load from this lack of overload capacity or the refusal of the gas engine men to operate their machines normally at part load; but there is another way out for the gas engine which has not been mentioned and which ought to be, and that is the possibility of cutting in and out of spare units on short notice. I know of seven units each of 2 000 h.p. capacity, that have been repeatedly, the whole seven, put on a load in three and a half minutes. There is no cylinder condensation to worry one. All one has to do is to pull the handle for the compressed air, give a twirl to the water valve, open the gas valve, and then carry load and obtain synchronism by the usual methods.

This method of handling the plant will not, however, take care of momentary wide fluctuations; the best method of doing this is, I think, that proposed by Mr. Stott.

C. C. Chappelle: There seems to be some difficulty in obtaining accurate information regarding the comparative operating costs of steam-turbine plants, the chief reason being that a large number of the turbines now in use form additional units in reciprocating-engine stations. I have in mind a plant of about 15 000 kw., the operating conditions of which are comparable with those in the large central power stations of New York city. This plant shows a record of 4.6 mills per kilowatt-hour for all operating and maintenance costs. To those familiar with the cost of power in large reciprocating-engine plants in New York, it is apparent that this figure practically coincides with Mr. Stott's deductions.

Though the combination of reciprocating engine and exhaust turbine makes a favorable showing, yet I believe that Mr. Stott's conclusions are based on rather an abnormally low result for a non-condensing engine, as this result comes within 85 per cent. of the theoretical consumption of a perfect steam engine operating between these temperature limits. Assuming 19 pounds of steam per indicated horse power as a fair cross-compound non-condensing engine performance, and 28 pounds of steam per indicated horse power as the performance of a low-pressure turbine—which approximates that shown by shop tests, with the moisture in the steam included—the net result approaches that obtained with a condensing turbine. The combination, however, possesses great advantages for enlarging existing engine stations, and for placing them on a more economical basis. It has already been adopted for a number of installations of this character.

While the gas engine has received less encouragement than the steam turbine, its development, nevertheless, has been no less progressive and, as indicated by this paper, it promises even greater things in generating power. A 500-h.p. gas engine was once looked upon as about the maximum limit for this class of prime mover; this is now considered quite an ordinary size unit.

Though the operation of 60-cycle alternators in parallel is not easily accomplished with steam engines, yet there are a number of gas-engine plants of large size in which 60-cycle alternators are operated successfully in parallel. The combination of gas engines and steam turbines possesses great advantages, as Mr. Stott says, and in several important prospective installations it is receiving serious consideration.

W. L. R. Emmet: The use of a low-pressure turbine in connection with the exhaust of a reciprocating-engine plant, or in connection with the waste heat of gas engines, naturally suggests itself to anybody familiar with the characteristics of the steam turbine. In a paper read at the Electrical Congress in St. Louis in 1904, I called attention to both these possibilities, and gave almost the same figures as to possible saving that Mr. Stott has given in this paper.

Among other things, Mr. Stott shows clearly the great saving in investment incident to the use of steam turbines. He gives a performance curve of a steam-engine that indicates an abrupt rise in the rate of steam consumption with increase of load. Capacity to carry the peak load is the controlling factor in the cost of a steam plant, and the reciprocating steam engine, particularly in the case of large units, is undesirable from this standpoint; for the reason that the problem in building very large steam engines is to take care of the great weights involved in the low-pressure cylinders and valves. Very large steam engines have a tendency to be uneconomical at overload, because the engine builder is tempted to make the low-pressure cylinder just large enough to give good economy at certain loads and so get through without mechanical difficulties. If this were a turbine of the good quality shown by another curve, instead of turning up at 4 000 kw., the curve given by Mr. Stott would either move out horizontally from that overload point or else it would turn upward slightly. The result would be that at some maximum boiler output, the turbine would give anywhere from 20 to 25 per cent. more output—more maximum plant capacity—than the reciprocating engine. In short, for so much money 20 per cent. more capacity could be obtained. The plant capacity is costing, in the case of this station, possibly $150 per kilowatt, 20 per cent. of that is $30 per kw.; in other words, the increased value afforded by the turbine in overload capacity is more than the total cost of the turbine. Disregarding operating expenses and considering only first cost, the engine can be scrapped and a turbine put in its place. In this station, then, if 20 per cent. were to be added to the capacity by erecting buildings, boilers, and other parts, the cost would be greater than if all the engines were discarded and steam turbines installed, and there would be no gain in peak-load capacity. And changing from reciprocating engines to turbines would also result in better economy of operation, as shown by the curves.

In regard to using a steam turbine in the exhaust between the engine and the condenser. In this case the turbine performs exactly the functions of a vast third cylinder on the engine, a cylinder of shape and size suited to the load; it receives this load without cylinder condensation, in fact with all the characteristics of an ideal cylinder. It is just another expansion working in the field which the reciprocating engine is incapable of filling, and in that field it can give as good efficiency as in any other field, and that efficiency closely approximates to that of a high-pressure cylinder. There has been obtained experimentally in the lower ranges of pressure, in a single process corresponding to the work of one cylinder in a steam engine, an efficiency as high as 76 or 77 per cent. with saturated steam in a very simple kind of steam turbine; this is as well as the engine does even in the higher ranges of pressure, and four times as well as it does in the lower ranges.

Suppose that an engine station is operated with engines limited in the matter of overload, by congestion in the low-pressure cylinders. Installing a low-pressure turbine between the low-pressure exhaust and the condenser, and assuming that the engine exhausts at a pressure of 20-in. vacuum, then 20 per cent. is added to the maximum output formerly obtained from the station. The capacity of the turbine to do that work is one-fifth of the capacity of the engine; it has no governor; it has only half the number of wheels and processes of the high-pressure turbine—altogether it is a very simple device. The turbine would cost possibly $35 or $40 per kilowatt; and the additional power produced, if rated at the cost of increase of capacity of the station, on an engine basis, would amount to something like five times the cost of installing the turbine. Consequently, enlargement by adding low-pressure turbines may cost only one fifth as much as an enlargement on the original line, and for the reasons explained the result is far better. As a rule, this can be done without enlarging the station or the necessity of employing additional men.

Obviously, the use of a high vacuum is important in turbine work, and efforts for obtaining this vacuum have met with astonishing success. And, too, a high vacuum is inexpensive to maintain; there is practically no leakage, resulting in a close approach to theoretical or ideal conditions.

Sometimes a reciprocating engine can be run non-condensing economically; but the advantage of condensation is so much greater with the turbine that the only reason for running non-condensing is the need of steam for other purposes. By installing cooling-towers in a non-condensing plant, the output can practically be doubled without adding to the operating cost.

F. E. Junge: Geographical, economical, or governmental conditions must always largely affect the point of view and the judgment on questions that are of common interest in engineering matters, especially when the comparison concerns the divergent practice of countries like United States and Germany.

An illustration of the extent to which electric centralization has been carried in Germany may be derived from the practice obtaining in isolated coal mines, which often possess no prime movers at all for driving the various pumps, hoists, fans, and other machinery. These mines have a transformer sub-station, equipped with motor-generators and fly-wheel sets, serving to equalize the load fluctuations, while high-tension electric current is obtained from a central station sometimes located in a city many miles from the mines. For instance, 50-cycle current of 10 000 volts is transmitted over a distance of 9 kilometers from the city of Essen to the Mathias Stinne Coal Mines, where 2 000 h.p. is used for driving the various machines. One coal mine which supplies good coal for coking purposes has a coke-oven plant attached to it and utilizes the waste gases thereof in a gas-engine-driven central station, while the surplus power is distributed by electric transmission to the sub-stations at neighboring mines.

This possibility of utilizing the energy in waste gases by distributing and selling it for light and other purposes in the neighboring industrial districts, forces the German engineer, in the determination of the commercial economic coefficient for a heat-power plant, to place a more pronounced value on the factor of heat cost than can be imparted to it under the conditions prevailing in this country. How seriously the difference in the valuation of this factor affects the prime mover problem in central stations can best be seen by comparing the estimated calculation made by Iffland to determine the respective merits of various engine drives for a combined coke, iron, and steel-smelting plant, where the coal mines are so closely located as to fall into the commercial distribution radius of the electric central station and are operated from it. The normal power required by all the engines is 42 200 h.p.; therefore the maximum simultaneous capacity which the plant must be able to carry permanently is 21 000 h.p., which is produced from the waste blast-furnace and coke-oven gases.

We shall consider only two cases: first, a gas-engine-driven central station; secondly, a steam-turbine-driven central station. All the auxiliary machines are operated from the central station. On account of the difference in consumption of the reversible and non-reversible machines, the total capacity of the central station required is found to be 25 000 kw., it being advisable with complete centralization to provide for an ample reserve. The power equipment in the first case consists of eight gas engines, each having 6 000 h.p. normal capacity, and 4 000 effective kw. (cos. ϕ = 0.8).

In the second case, of five steam turbines each having 10 000 h.p. normal capacity and direct connected to alternating-current generators of 6 800 effective kilowatt capacity (cos. ϕ = 0.8). The normal capacity of the gas-engine-driven central station is therefore 32 000 kw. total, and of the steam-turbine-driven station, 34 000 kw. Most of the machines used on the plant are in constant operation all the year round.

Now, assuming that the waste gases have no commercial value whatever, then the actual cost, including initial capital outlay and operating expenses for generating one boiler horse-power hour, is as follows:

For gas-engine-driven central station.................	44 cents
For steam-turbine-driven central station..............	42 cents

For purposes of comparison, I give the figure that would be obtained with steam-engine drive all over the work. One boiler horse-power hour would then cost 75 cents. In this case, then, the steam turbine would be the most economical prime mover, However, the assumption that the blast-furnace and coke-oven gases are given for nothing is erroneous. The gases must first be cleaned, as this increases their heating capacity and makes them applicable for use in gas engines; but this process requires an expenditure of one cent per 30 000 cu. ft.; moreover they actually have a value as fuel for steam raising. In the plant under consideration, we shall therefore compare the power value of the waste gases when used in gas engines to what obtains when burned under boilers, and so must appraise the gas at a rate corresponding to the reduction of the coal bill. If power can be distributed abroad, the appraising of the gas depends on the disposal of the surplus power and varies with the locality. Now estimating coal at $2.50 per ton, and assuming that seven kilograms of steam are raised from one kilogram of coal, then the value of the blast-furnace gases which are to be used in gas engines is $150,000. The value of the blast-furnace and coke-oven gases available for raising steam is $325 000. With this valuation, the former results are modified as follows:

Gas-engine-driven central station, 54 cents per boiler h.p. hour.
Steam-turbine-driven central station, 66 cents per boiler h.p. hour.

With steam-engine drive the cost would be 98 cents. It will be seen that the correct valuation of the fuel upsets the former results entirely in favor of the gas-engine-driven central station. Basing the results on the cost of production per ton of marketable goods, of which this plant sells 300 000 tons per year, we arrive at the following:

Gas-engine-driven central station, $2.00 without, and $2.48 with appraising the gas.

Steam-turbine-driven central station, $1.93, and $3.02 respectively.

With steam-engine drive the cost would be $3.35 and $4.42 respectively.

It is seen that the gain effected by the selection of gas engines instead of steam turbines for the central station amounts to 50 cents per ton of annual capacity. The figures are of special significance, as they show how much the whole prime-mover question hinges on the valuation of the factor of heat cost. The conditions change, of course, if a plant possesses only capacity for iron and steel smelting, and has rolling mills but no coal mines attached to it; and they are again different for a steel plant with rolling mills but without coal mines, blast furnaces and coke ovens. It is only in the last named case that gas-engine drive—gas engine-central station and scattered gas-engine auxiliaries—is the most economical method, but it is only by a combination of coal mines, blast furnaces, steel smelting plants, and rolling mills that an efficient production is possible, as we can hereby avoid paying the duty imposed by the protective tariff on raw materials, pig iron, and half-finished goods.

Sight must not be lost of the fact that the results of the above calculation are based on foreign conditions and cannot be used for direct comparison with the corresponding items which for the same plant capacity would obtain in this country. This, however, does not affect their relative value in the least.

Owing to the need of reducing waste in technical methods, and to the geographical and social conditions prevailing on the Continent, which differ from those in this country as regards the distribution and production of mineral and metallic ores, the density and sphere of action of industrial centres, and the cost and reliability of skilled labor that can be secured, we shall —if the surplus power that becomes available by the adoption of economical prime movers can be used in the works, where its value is equal to the corresponding reduction of the coal bill, or if it can be sold to advantage abroad, where its value varies with the local conditions—invariably select the gas engine as prime mover for central stations. Where there is no market for available surplus power, there the steam turbine will always keep its field of usefulness.

Calvert Townley: In connection with the study of economy in steam usage, the conditions affecting a moderate sized plant should be considered as well as those obtaining in a very large plant. In that connection the use of exhaust steam for heating purposes should not be lost sight of.

In the majority of isolated plants, in many electric light stations, and not infrequently in railroad power houses, opportunity could be made, if the plant were originally so designed, to utilize for seven months of the year a large part, if not all, of the exhaust steam for heating; thus, in effect, turning the generating plant into a heating plant, and using the engines as reducing valves to lower the steam pressure from that generated by the boilers to that required for the heating system.

The B.t.u. in steam at 175 pounds gauge pressure is only 5.45% more than in steam at 10 pounds gauge pressure, so that, given the necessity for a steam-heating plant, the additional coal required to make the steam available for electric generation is comparatively small.

Some unfortunate experiences in an endeavor to utilize exhaust steam for heating, where either the circumstances or the design of the plant, or both, were unfavorable, have discouraged many engineers from the more general adaption of this principle; but there can be no doubt that it is susceptible of wide application, and that the possibilities of saving are very great.

Mr. Stott's Table No. 1 is extremely interesting, as showing a careful analysis of loss distribution. It should be noted, however, in considering this table, that the last column shows the losses in per cent. of the original heat units in the coal, and, therefore, it does not represent a true measure of the relative importance of the losses; for example, the loss in engine friction is given as 0.8%, whereas there has been 38% of the energy lost before reaching the engine, and the engine friction is, therefore, approximately 1.3%. Similarly, the heat units rejected to condenser are given as 60.1%, whereas 29.3% having already been disposed of, the condenser takes over 86%; that is to say, the efficiency of each transformation increases in importance as we come down the line, and, therefore, a small gain in efficiency in a late transformation may be of more value than a considerably greater gain at an earlier stage.

Hartley Le H. Smith (by letter): In discussing the operation of hand-fired and stoker-fired boilers, Mr. Stott in Figs. 6 and 7 illustrates various items as a function of the draft, which is presumably the draft at the boiler downtakes, although he does not explicitly say so. The values of draft are so much lower in Fig. 7 than in Fig. 6 that it is not quite certain whether the draft was measured at the same place in the two cases. In Fig. 6 the maximum economy is attained at only 77% of the standard rating, and the economy at the standard rate of evaporation shows a falling off of 13% from the maximum value. As these conditions are rather extraordinary in a boiler rated at 600 horse-power, in which the ratio of heating surface to grate surface is usually high, it would be interesting to know in what manner the variation of draft at the downtake caused the draft immediately above the fire to vary, and also the corresponding variation of CO_2.

The variation of reciprocating-engine steam consumption shown by Mr. Stott in Fig. 8 is extremely interesting and important. A feature even more significant than the rapid rise in the most economical steam consumption, is the very great extravagance in steam consumption which results from an engine with its load equally divided between the cylinders, and the extraordinary rates at which this consumption with such adjustment increases from a point representing a little over 80% of the rated load. In Mr. Stott's illustration the equal division of load between the cylinders makes the consumption at rated load 3.5% higher than the most economical adjustment, and at 35% overload the equal division between the cylinders consumes 9.5% more steam than the most economical adjustment. Mr. Stott might have stated which cylinder was doing the most work, and in what manner the ratio varied throughout the range of load he has illustrated. The natural inference is that the most economical working was obtained by putting the larger share of the work on the high-pressure cylinder, for the avoidance of the large cylinder condensation losses at heavy loads in the low-pressure cylinder. A hint in this direction is given in speaking of the reciprocating engine with a low-pressure turbine on its exhaust, that the reciprocating engine should be run high pressure where relatively it is most efficient. It seems probable that a good many operators of reciprocating engines should take Fig. 8 with considerable seriousness, as there are probably many more engines operating with the load equally divided than unequally divided in such manner that the minimum steam consumption results.

There is another factor of some moment; namely, if it is not assured that engines are working with the most efficient valve adjustments, it would not pay in a large system to operate large units at excessive overloads during the periods of maximum demand rather than smaller units at rated load in older stations held normally as reserve equipment.

The author says that the apparent saving of 13.5% in steam consumption when a turbine is operated with steam superheated 200°, means an actual thermal saving of only 6.6% due to the greater total heat of superheated steam. It seems essential to add that if the superheating is obtained with internal superheaters, as is usually the case, there is an almost inevitable increase in the heat loss escaping to the stack, due to the increased temperature of the gases; that this increased heat loss may easily become of serious moment may be seen in Fig. 5. In the absence of economizers it is conceivable that this item might wipe out the saving due to the use of superheated steam in the turbines.

In Mr. Stott's treatment of a high-pressure reciprocating engine with a low-pressure turbine on its exhaust it is difficult to see how the giving up of 165.3 B.t.u. per pound of steam is connected with the expansion of steam from the absolute pressure of 190 to 14.7 pounds per square inch, except that as the generator has an efficiency of 98%, and the engine a mechanical efficiency of 93.65%, the over-all efficiency is 91.75%, which would require $\frac{3412}{0.9175} = 3\,718$ B.t.u. in the engine cylinder per kilowatt-hour. When this is increased by 13.5% to allow for radiation, incomplete expansion, and similar losses it becomes 4 215 B.t.u. per kilowatt-hour, which when divided by 25.5 pounds, gives Mr. Stott's figure 165.3 B.t.u. per pound of steam. The thermal efficiency represented by the expansion of steam between the limits of 190 and 14.7 pounds per square inch absolute pressure is 19.7 per cent.

DISCUSSION ON "POWER PLANT ECONOMICS," AT PITTSBURG, PA., FEBRUARY 13, 1906.

P. M. Lincoln: In regard to electricity-driven versus steam-driven auxiliaries, it seems to me that the two considerations which should govern are: first, economy; secondly, reliability.

I agree with Mr. Stott that the economy of the steam-driven auxiliaries is greater than that of the electricity-driven auxiliaries. The only objection that can be raised is the extensive steam piping required by the steam-driven auxiliaries; this piping will have considerable radiation which cannot be avoided, and if the steam piping to the auxiliaries becomes too extensive, the loss from this cause may be greater than the amount of inherent economy. Any operating engineer will take the type of auxiliary which is most reliable. As between reliability and economy the operator will invariably choose reliability.

As to direct- versus independently-driven exciters, I will mention only the most salient points. The considerations which should govern are those of economy and reliability. As far as economy goes, there are three ways of driving the exciters; one is to connect it directly to the generator shaft, a second is to drive it by a separate prime mover; and the third is to drive it by a motor which is driven by the main prime mover. These methods differ in economy by as much as the main prime mover differs from the auxiliary prime mover.

As far as reliability goes, one point is that of regulation; on that point the motor-driven and the direct-connected exciters are at a disadvantage, because any variation in speed of the main plant is reproduced in the exciter, which alters the voltage of the exciter in a ratio faster than the speed alters in the main generator. This causes a variation in the voltage of the main plant considerably greater than the original speed variation.

W. E. Moore: Power station design does not depend on coal economy only or even on operating cost, but on the very important factor of total cost per unit output as determined largely by the fixed costs on investment. These are a constant expense regardless of the plant load-factor, resulting in a variable cost per unit output decreasing with an increasing load-factor and becoming a minimum when the load-factor reaches 100%, or when the plant carries a full load for every hour in the year. It is therefore obvious that the character of the plant must be governed largely by the load-factor.

According to Mr. Stott, there are delivered to bus-bars 1 452 out of 14 150 B.t.u., or 10.3% thermal efficiency. It is interesting to note that the regenerative recovery in the entire plant is 3.1% credited to the feed-water heater, and 6.8% to the economizer. Ordinarily there should be some heat recovered through the feed-water taken from the hot-well, but in this case none seems to be considered, probably because the injection-water is brine and city water is used exclusively for feed.

I would call attention to the demand for larger boiler units caused by the introduction of the steam-turbine, whose relatively small floor space makes a compact boiler of great desirability. It is not to be forgotten that the smaller the number of boiler units, the less attention they require; and the cheaper their cost of installation, piping, and maintenance becomes. Mr. Stott calls notice to the equal efficiency of all types of boilers when worked under like conditions. In getting at the results of bad firing it is only necessary to analyze the stack gases with one element in view, CO_2, and the nearer the approach to 14% the better the firing becomes. Take a boiler with a given amount of heating surface, and pass the gases over with a given velocity, the same efficiency is obtained no matter what the type of boiler.

Boilers are especially desirable which are simple to repair and clean and which will give dry steam. Wet steam is a common evil of the power station. For each 1% moisture in steam the efficiency of turbines is reduced about 2% and the capacity more than correspondingly reduced, while in the case of engines the economy is not so much reduced but the lubrication of internal parts is much more costly, to say nothing of the greatly increased danger from accidents.

The almost universal adoption of water-tube boilers brings with it the corresponding disadvantage of more moisture in steam, and if for no other cause than this, the elimination of moisture from steam would demand the installing of superheaters in the modern steam power plant, especially for turbine work.

There has recently been brought out in the United States a new form of steam boiler of the water-tube type especially adapted for units as large as 1 000 h.p. This new boiler seems to eliminate troubles from differential expansion of its various members, and is peculiar in that it is practically self-cleaning so far as internal scale is concerned. Being adapted for firing from both ends, there are no size limits determined by grate area.

Mr. Stott shows that 3.1% is recovered by the feed-water heater. He therefore concludes that the auxiliaries should all be steam driven so as to obtain sufficient exhaust to heat the feed-water. This brings up the question of steam- versus electricity-driven auxiliaries. I do not believe that either system will prevail to the exclusion of the other. The ideal arrangement seems to be direct-acting steam-boiler feed-pumps and possibly centralized vacuum-pumps with all of the smaller and scattered auxiliaries such as service-pumps, oil-pumps, hot-well pumps, circulating-pumps, coal- and ash-conveying machinery, etc., driven by electric motors. The power supply for the motors to be furnished by separate steam-driven exciter sets of sufficient capacity to carry the excitation plus the motor load, and exhausting into feed-water heater along with the boiler feed-pumps and centralized steam vacuum-pumps. For reliability and low first cost, nothing is better for boiler feed-pumps than a direct-acting steam-pump, and the same statement applies to centralized vacuum-pumps. These, with exciter sets, can be located near the boilers and feed-water heater so that there will be a minimum of steam and exhaust pipes to and from them.

It is hard to explain the expense of a piping system for a small steam plant; a steam pipe when it is once installed has to be kept hot all the time, has to be kept drained, and every steam-supply pipe must have an exhaust pipe, so that the trouble is far greater than the expense.

The motor-drive for the other auxiliaries permits of direct connection to centrifugal pumps, making very compact, cheap, efficient, simple, and easily maintained sets, and entirely eliminates the maze of hot steam and exhaust pipes which permeate the ordinary power-plant basements and which are such a continuous source of trouble and expense to keep covered, drained, joints tightened, etc. Motor-driven sets also do away with the necessity for cylinder lubrication, oil-cups, and nearly eliminate the small stuffing-box and packing expense and resulting slop from steam-pumps. Since the exciter sets must furnish the power, there is no diminution in the supply of exhaust for feed-water, and since the power is direct current there is every opportunity for efficient speed regulation to meet all variable load demands. Therefore there seem to be very valid reasons why steam-driven auxiliaries should not be used exclusively, but rather to use motor-driven auxiliaries in the larger number of cases.

My opinion seems to be directly contrary to the opinion of Mr. Stott, but I think his opinion is probably based on some accidents that occurred at the Manhattan plant. I understand that when the plant was first started they put in motor-driven boiler feed-pumps, and on one occasion a short circuit resulted in the closing down of the plant; before the engines could be started up the boilers had evaporated all the water out of the valves.

With reference to the use of superheated steam, it should be said that superheat causes no additional lubrication expense on the turbine, such as is necessary with high superheat in engines.

The author calls attention to the turbine's much flatter efficiency curve, which means better all-day efficiency, and to the fact that the turbine set's first cost is 33% less than that of the reciprocating-engine set. These two features, as will be seen later, have a very marked bearing on the total cost of the unit output, especially when the plant works on a low load-factor. It should be noted in this connection that the ordinary power plant works on a load-factor of about 50% or less, usually less, frequently as low as 25%.

It is often charged against the turbine that it must have an expensive surface condenser with auxiliaries using larger amounts of power to maintain its necessarily better vacuum for maximum efficiency. Practice has, however, in some of the more recent constructions, shown both ideas fallacious, as high vacua are easily maintained in turbine plants with ejector or barometric condensers, and there is far less air leakage into the turbine exhaust. Which type of condenser to install is determined in nearly every case by the suitability of the available water for boiler-feed. The surface condenser can be used with advantage on turbines more often than on reciprocating engines, as the turbine introduces no oil into the exhaust, and the condensation is therefore most suitable for feed water.

Mr. Stott estimates that the combined engine and low-pressure turbine plant would use 23% less steam per unit output. Such an increase of economy in practice appears to be improbable. It would seem that a plant containing such combination sets would be much more complicated, more expensive in first cost and maintenance, and that a lower total cost per unit output would probably result by the installation of a straight turbine plant.

The accompanying chart plotted on the same scale on a basis of total plant efficiency in B.t.u. per kilowatt-hour for steam-engine, steam-turbine, and gas-engine sets shows clearly the relative economical capacity range of the three types of prime movers cited by Mr. Stott. While the gas-engine curve is not so flat, it should be remembered that the economical capacity range of the producer and auxiliaries for a gas-engine power plant is much broader than for steam boilers with the usual steam power plant auxiliaries, which tends to flatten out the curve for economy of producer-gas engine plant at various capacities.

The economy of the gas-engine plant is so much better than that of the steam plant that a far greater variation from maximum economy with change of load can well be allowed and still keep the plant duty far higher than any type of steam plant.

There seems to be an error in Mr. Stott's assumption that the entire 30% waste heat in gas-engine exhaust, minus 5% loss to stack, can be converted into steam. The engine exhaust-gases being at a comparatively low temperature (as compared with ordinary boiler furnace temperature) cannot impart even the ordinary percentage of heat to the boiler; therefore more than the usual loss of heat to stack must be allowed. This would probably reduce the proportion of heat saved from exhaust gases below 15%. Neither is it proper to assume that the 7.1% of jacket-water heat could be used in the turbine end of the combination plant at a thermal efficiency of 35.1%, for almost the exact temperature of feed-water is available in the condensed steam from turbine so that the warm jacket-water would scarcely be used for the boiler-feed.

The recoverable heat could not therefore amount to 37.1% nor could the efficiency of its conversion run so high as 35.1%, nor could the thermal efficiency of the turbine end of the combination plant approach 25%, as stated by Mr. Stott; especially since the turbine end of the plant would be carrying a very variable load which would decrease its steam economy correspondingly.

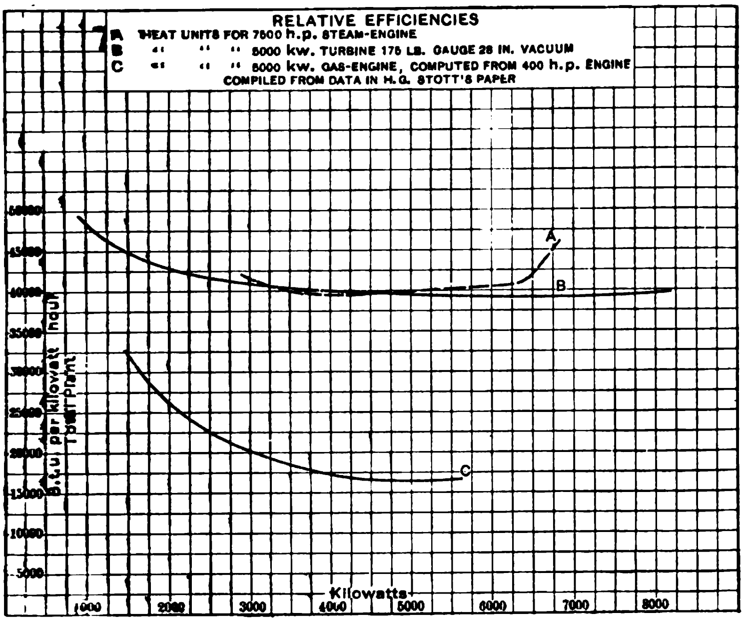

Fig. 1.

There seems good prospects of our having at an early date a commercial gas-engine that will have overload characteristics approaching those of the steam-engine and will therefore show much better average efficiency on the customary load variation.

The Otto cycle gas-engine exhausts its gases at a terminal pressure, say 40 lb., when carrying from 50 to 100% load. The ideal gas engine cycle would seem to embody a design in which the terminal pressure would vary with the load, as in a steam engine, and the combustible mixture would be varied in volume according to the load; at light loads a stratified cushion of air being first admitted next to the piston to make up a constant cylinder volume and therefore a constant compression irrespective of load. The compression space or clearance to be much smaller than usual, so that the usual high compression would be maintained with the intake gases following the piston, say half the stroke. The full-load engine capacity would then be so proportioned as to expand the burnt gases down to say 5 lb. before exhausting, while at the overloads the governor would admit sufficient explosive mixture to maintain the terminal pressure much later so as to exhaust at, say, 40 to 50 lb. per square inch. Thus the terminal pressure would vary with the load much as is the case with a steam-engine. This in contradistinction to the variable compression pressure with load changes in the ordinary Otto cycle engine. In a gas-engine of the type suggested the temperature of the exhaust at average load would be lower, and less heat would therefore be available for steam raising, possibly not more than would be necessary for steam supply to producers and auxiliaries of the gas generator room, so there would be no reason for mixing gas-engines and steam-turbines in one station. The plant-duty of a station of this type should be far greater than that of a mixed plant, not to mention the simplification of operation and maintenance.

I think it is a very important matter not to mix the equipment in any power station. As Mr. Stott has pointed out, it is difficult to maintain a state in the boiler room where the stack losses are kept as low as 22%; as a matter of fact it runs over 30% in this district, instead of down as low as 22%. Mixing equipment means simply reducing the chances of keeping it down to that point, and furthermore, there is every reason why a plant should be kept uniform.

In conclusion, it is evident that we cannot longer, under ordinary conditions, afford to install steam-engine electric power plants; for turbine plants are more efficient and cheaper in both investment and operating costs, though producer-gas engine plants are far cheaper than either in operation but not in first cost. There is, however, good prospect of lower first cost and better overload characteristics in the near future.

Low investment cost is an essential for plants operating on a low load-factor, but it does not seem advisable to mix gas-engine and turbines in the same plant, but rather to encourage manufacturers to develop a gas-engine operating on a cycle that will permit of developing at least 50% overload, the engine being rated at its most economical load.

Rudolph Wintzer: A large number of electrical central stations in Europe are owned by municipalities, as are many of the city gas-works. In early years the gas-works frequently furnished gaseous fuel to small gas-engine driven plants, the charge for gas having run as high as 85 cents per 1 000 cu. ft. But during the last five years several large central stations have been established, using producer-gas engines. Scheveningen, a bathing resort in Holland, will ultimately be equipped with six 350 h.p. Nurnburg gas-engines driven by anthracite producers of the suction type.

The largest power plant using producer-gas is located in Madrid, Spain, furnishing light and power to the entire community. It is equipped with six 1 250 kw. (2 000 h.p.) Nurnburg gas-engine alternators operating in parallel, supplied by a Mond producer-gas system using low-grade slack coal. Recovery of by-product, including tar and ammonia, is practised at this 12 000 h.p. plant.

The gas-engine is used to a very great extent with suction producers, in water-pumping stations for small cities and counties, especially in western Germany. " Braunkohle " (corresponding to our peat) and lignite in the form of briquettes are largely used in these small plants, and with excellent results.

The greatest development of the gas-engine on the continent has taken place in connection with blast-furnaces and the coaling industry where the waste gases from furnaces and coke-ovens are largely used for power. A large enterprise of this character is now being carried out near Essen in Rheinland. Essen is the Pittsburg of Germany. Within a radius of 40 miles occur most of the largest coal mines and iron and steel works of that country. Most of the existing electrical central stations in the district have been acquired by the steel syndicate, which is erecting large central stations driven by blast-furnace and coke-oven gas to furnish this whole industrial section with electricity for lighting, power, and traction. Some customers in the territory have requisitioned as high as several thousand horse power. These central stations will be erected at the various steel mills and mines, and will all work in parallel.

Typical gas-power stations using blast-furnace gas, are now working at the following plants: John Cockerill Co., Seriang, Belgium, 3 000 kw. United Iron and Steel Works at Hoerder, Westphalia, 3 500 kw. Schalker Iron and Steel Works, Gelsenkirchen, 4 000 kw. Rombacher Iron Works, 3 000 kw. A typical plant driven by coke-oven gas is located at Eschweiler mines in Alsdorf, where a central station of 2 800 kw. is in service, using Otto coke-ovens with recovery of by-products. This plant furnishes current for driving 3 000 h.p. main hoisting engines, pumps, fans, compressors, coal-washing plants, etc., and for electric traction service in the neighborhood. No steam is used at these works, and a producer-plant is available as a reserve in case of necessary shutting down of the coke-ovens. In a short time this plant will work in parallel along high-tension transmission with a hydraulic plant 40 or 50 miles distant, installed by the Ruhr River Hydraulic Development Company.

While formerly the practice was to drive large rolling-mills directly with large gas-engines, the present practice is rapidly tending to motor-driven rolls, supplied with power from a central station. At Differdingen, in the steel and coal works of the Germany & Luxemburgh Steel & Mining Company, it has been found by careful experiments that for every 1 000 h.p. maximum required at the main rolling-mill, with engine-driven rolls, only 600 h.p. capacity is required at a central station. A number of units are provided, giving flexibility of service, and 40% is made on the first cost of the gas-engines installed.

TYPES OF GAS-ENGINES IN USE.

For large work three types are represented; namely:

1. The four-cycle, double-acting tandem engines of Nurenburg, Deutz, and Cockerill.
2. The two-cycle, double-acting Koerting type.
3. The two-cycle, double-acting opposed, Oechelhauser engine.

Of these three types, the four-cycle type has become standardized for general power-station work, while the two-cycle types have found their most extensive applications to blast-furnace work. Four-cycle tandem engines are operating up to 2 000 h.p.; that is, 1 000 h.p. per cylinder. Two-cycle engines have also been built from 750 to 1 000 h.p. per cylinder.

Comparing the constructions of the three types for 1 000-kw. units, it is found that the four-cycle engine has one connecting-rod and two power cylinders; the Koerting engine has two connecting-rods, two power cylinders, four compressor cylinders of nearly the same diameter, and two side connecting-rods; the Oechelhauser two-cycle engine has a six-throw crank-shaft, four bearings, six connecting-rods, four single-acting pistons, and two compressor cylinders. In the Koerting engine the exhaust ports in the cylinder wall are uncovered by the piston; in the Oechelhauser engine the pistons uncover both exhaust- and air-ports so that no valves are used. This elimination of valves in the Oechelhauser and Koerting types looks at first sight like a simplification, but in reality it involves serious complications in the number and disposition of the principle working parts.

A comparatively new type of engine is being built by a British company. It is a two-cylinder double-acting vertical engine arranged like a cross-compound steam-engine, with generator between cylinders. This is built up to 2 000 h.p. capacity.

European practice has definitely tended toward single-crank units, and the horizontal tandem, double-acting type has become the standard in this respect. By duplicating the tandem arrangement, making a two-crank engine, the economy is not improved. The speed variation of the single-crank type is found to be close enough for alternating-current work. The single-crank units give far greater flexibility in central-station operation; they can be loaded more economically, and there is more opportunity for inspection and repairs. The sizes most frequently used are 1 000, 1 500, and 2 000 h.p.

ELECTRICAL OPERATION.

In regard to the electrical specifications for gas-engine work, Continental firms usually specify a cyclical fly-wheel deviation of $\frac{1}{40}$ to $\frac{1}{60}$ the pole-distance in engines with one impulse per stroke. This condition can easily be met, and takes into consideration occasional irregular working. In a 500 h.p. engine of the vertical, double-acting type, driving spinning machinery at the Hollins Mills, Marple, a cyclical speed variation of 0.2 to 0.4 per cent. was obtained, which was increased to only 1 per cent. when one cylinder was made to misfire regularly. The cyclic speed variation was taken with a very sensitive and well-made recording tachometer. It is a matter of interest that the steam-engine which formerly did the work of this gas-engine showed 8 per cent. cyclic variation, and it is not surprising therefore that the mill tenders had less trouble from broken threads after the gas-engine was put in service.

Troubles from parallel operation are practically unknown in engines above 1 000 h.p. giving two impulses per revolution and 25 cycles.

A type of alternator in general favor, is a combined fly-wheel and generator field in one structure, with the fly-wheel rim outside the rotating field. With the usual speed of periphery of field, this permits a high fly-wheel speed with a short distance between the bearings and good accessibility.

FUELS.

In Germany the cost of hard coal is $5.50 to $6.50 per metric ton, (2 220 pounds), according to facilities of transportation. Good bituminous coal costs $3.50 to $5.50 per ton, and bituminous slack costs from $1.50 to $2.50 per ton delivered at the plant. On a small scale anthracite is largely used, but in very large plants, such as that of Madrid, low-grade bituminous coal is mostly used. The Mond producer system has greatly enlarged the possibilities of low-grade bituminous fuels.

Clean gas is the first consideration for successful running in all power plants using producer-, blast-furnace, or coke-oven gas. Tar in its several forms, must be removed from the gas, also sulphur and dust, to a point where not more than 0.03 grams per cubic meter of foreign matter is present.

ECONOMY.

With blast-furnace gas the 1 000 h.p. engines at Rombach and Ruhrort have shown a heat consumption as low as 9 300 B.t.u.'s per brake horse power hour at full load, and 12 000 at half load, using the " lower " or " effective " heat value of the gas. It is European practice, however, to rate engines somewhat higher than they are rated in America; the above engines having only 5 per cent. normal overload capacity. High-grade Mond gas-plants in England have shown economies of 1.1 to 1.2 pounds of slack coal per brake horse power hour, including all standby losses for the balance of a 10-hour working day In this particular the producer has a very large advantage over steam, and especially superheated steam plants, as the standby losses are almost negligible. At a large European iron and steel works at Essen extensive tests were made to ascertain the standby losses on the steam-piping system which was in fair condition and completely lagged. With no steam used for driving engines it was found necessary, in order to maintain normal pressure, to keep twenty 180-h.p. boilers under full fire.

In well-constructed horizontal gas-engine plants the oil consumption is no higher than in a corresponding steam-engine plant. For instance, a 1 000-h.p. tandem gas-engine requires on an average of 35 to 40 lb. of oil (4.75 to 5.25 U. S. gal.) per 24 hours, 60 per cent. being cylinder oil at 35 cents per gallon, 40 per cent. being engine oil at 20 cents per gallon.

COST OF EUROPEAN PLANT.

For a 2 000-h.p. high-grade gas-engine plant the distribution of cost should be about as follows:

	Dollars per brake horse power
Gas-Engines	$30.00
Foundations	2.20
Auxiliaries	0.80
Building	4.00
Piping and engine outfit	3.00
Electrical outfit	14.00
Gas-producer plant	14.00
Producer house	1.50
Total	$69.50

or very nearly $100.00 per kilowatt.

About a year ago high-grade gas-engines sold for about $25.00 per brake horse power. The present prices are somewhat higher. For high-grade steam-engines using superheated steam the cost is about the same, $25.00 per brake horse power.

J. R. Bibbins: As the saturation and regulation curves of a dynamo are characteristic of its operation, so do certain curves as definitely characterize the working of a prime mover. Speaking particularly of heat engines, there are three curves which materially assist in determining the suitability of a machine for a particular service; these curves represent: 1, the hourly heat (steam or gas) consumption at various loads with its derived curve of the " water-rate " variety familiar to steam-engine practice; 2, kinetic (absolute thermodynamic) efficiency, with its derived curve of mechanical efficiency; 3, speed regulation, involving, in the case of the reciprocating-engine, cyclical as well as absolute speed-variation. The first determines the rate of input of working medium, steam, gas, air, etc.; the second, the efficiency of conversion into useful work in the shaft; and the third, the suitability of the machine for operating constant-potential electrical apparatus. In this discussion we are chiefly concerned with the first, and from a purely practical standpoint.

Steam-Engines: In high-speed steam-engines such as the Willans, governing by throttling steam-pressure, the total steam consumption per hour is practically proportional to the load. Plotted in the form of a curve, known as the " Willians "* or water line, it gives practically a straight diagonal line *A B*, Fig. 1.

The so-called water-rate curve derived from this, *A' B'*, and expressing steam used per horse power per hour is, then, of course, a hyperbola and shows a constantly decreasing water-rate with increasing load. Clearly, then, this type of engine is able to give its best economy at maximum output. In modern power work, however, this condition is demanded only occasionally to tide over maxima in a fluctuating load; on the other hand, from an economical standpoint, the engine is obliged to work at considerable disadvantage during normal loading.

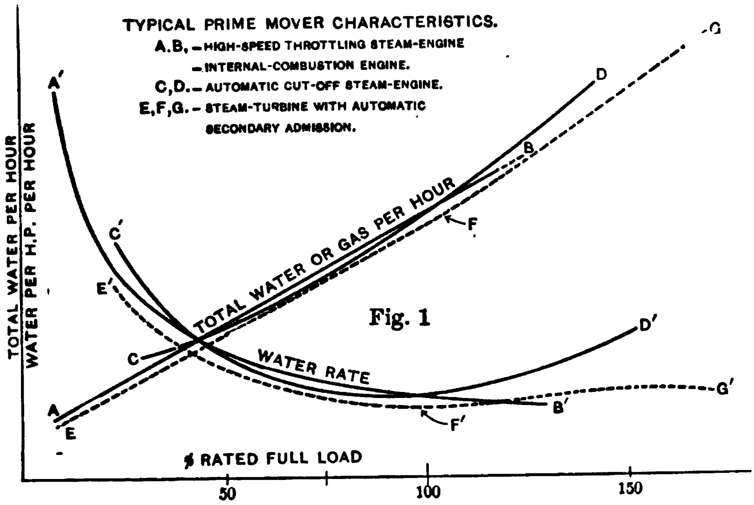

Fig. 1

Now in a steam-engine governed by a positive cut-off, the water-line is decidedly curved, *C D*, due to a variety of causes, giving a water-rate curve *C' D'* of more pronounced curvature. Two important results have, however, been achieved; first, the engine gives its best economy between three-fourths and full load where it is normally working a greater part of the time; and secondly, by lengthening the cut-off a very large overload capacity is available. On the other hand, the cut-off method

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* " Willans Law " first expounded by P. W. Willans. See *Transactions* British Institution Civil Engineers, 1890.

compares less favorably at light loads and heavy overloads, the water-rate increasing rapidly in either direction.

Steam Turbines: Manifestly a combination of the two systems should yield the characteristics most to be desired; these characteristics are: *a*, maximum economy at normal loading; *b*, large overload capacity with fair economy; *c*, good economy at light loading. These have fortunately been realized to a large extent in the steam-turbine.

A steam-turbine of the well-known pressure type gives a practically straight water-line, *E F*, Fig. 1, up to about full load with a somewhat higher inherent efficiency than the steam-engine, in most cases exceeding the cut-off engine even at the best load. By the use of a " secondary " admission of steam to lower stages in the turbine, its power may be increased to as high as double the normal rating and with but small loss in economy. Supposing the secondary or overload valve comes into action about full load, *F*, the water-line abruptly changes direction, *F G*, resulting in a compound water-rate curve, *E'F'G'*. At the point of opening, *F'*, the steam consumption begins to increase, but as the overload increases the turbine tends to regain its original efficiency. Furthermore, the prime mover and generator are better matched in regard to efficiency than in the cut-off engine, both doing their best work at normal rating.

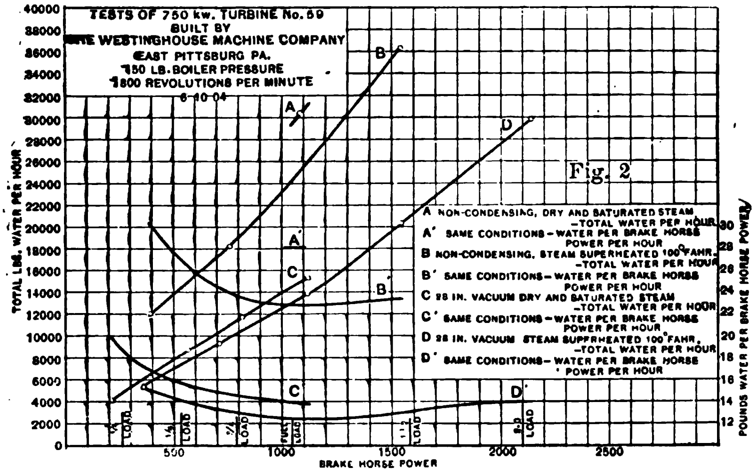

Fig. 2

These characteristics are well illustrated in the accompanying curves, Fig. 2, showing tests upon a 1 000-h.p. Westinghouse-Parsons turbine. From one-half load to 100% overload the water-rate varies but little over 10%. The same characteristics appear in the non-condensing tests, except that the turbine is unable to sustain as heavy a load, being guaranteed only for full load non-condensing and 50% overload condensing.

Low-Pressure Turbines: If we represent in curve form, Fig. 3, the work available in steam expanding from 150 lb. initial pressure to atmosphere, the tact is apparent that there has been used only about one-half of the total work available at a vacuum of 28 in. This at once explains the possibility of the low-pressure steam-turbine working on vacuum alone, and it is interesting to note that the water-rate of such a turbine is about double that of a similarly constructed turbine working through the entire range of pressure. Thus a 750-kw. Westinghouse-Parsons turbine below atmosphere has given a water-rate of 25 lb. per brake horse power with high vacuum, corresponding to about 13.5 lb. per brake horse power-hour for the total pressure-range. Moreover the total water-line is practi-

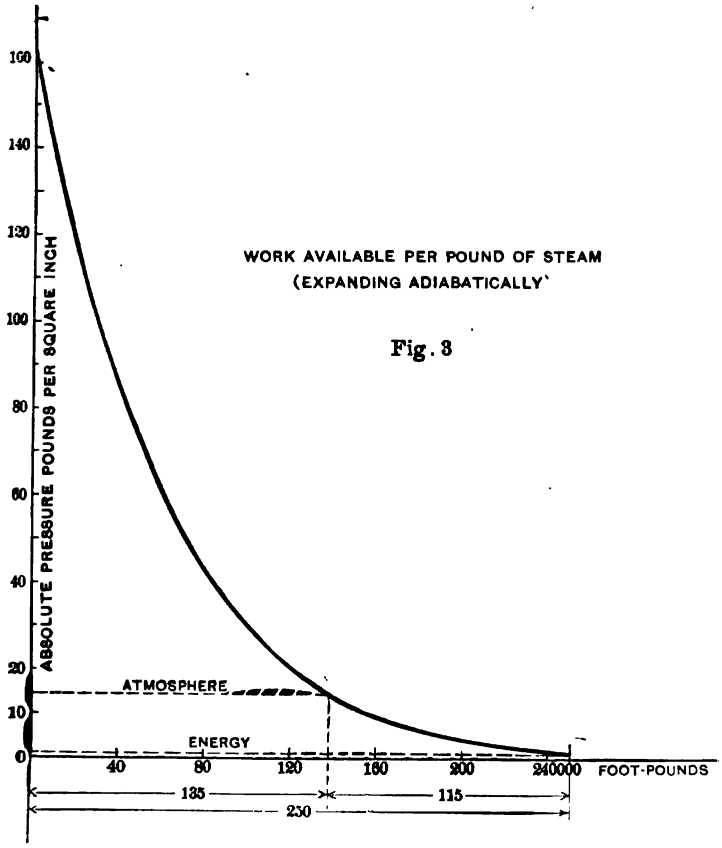

Fig. 3

cally straight as in the normal turbine, showing that steam is used with uniform efficiency at all loads. Professor Rateau of Paris has done much along these lines of low-pressure turbine work. The low-pressure turbine is of interest in providing a means of nearly doubling the output of a non-condensing steam plant with but little increase in operating expense. Cooling-towers are, of course, of assistance where water is costly.

High-pressure turbines, working down to atmospheric pressures, are, on the other hand, frequently used in district heating systems, half of the energy in the steam being converted into electrical energy, and the remainder into heat. Usually, a condensing turbine is employed running non-condensing during cold, and condensing during warm weather.

Internal-Combustion Engine: Curiously enough, the gas-engine presents the same characteristics as the throttling steam-engine; namely, a nearly straight Willans or gas-line, *A B*, Fig. 1, and a continually decreasing rate curve of gas consumption, *A′ B′*. It possesses, however, nearly double the efficiency of heat conversion or kinetic efficiency* of the steam-engine. An engine of good design is capable of delivering from 25% to 30% of the heat of the gas in the form of work at the shaft, while the corresponding kinetic efficiency of a large steam-unit usually runs from 12% to 15% and of a steam-turbine 15% to 22% of the heat input. As a machine, its mechanical efficiency is nearly the same as a high-grade reciprocating steam-engine.

Could we rate the gas-engine at its maximum capacity we should, of course, obtain maximum efficiency at normal rating, and in European practice this is frequently done; but in American practice some overload capacity is demanded, hence we must deliberately rate the engine below its maximum by the per cent. of overload desired. This is an unfortunate characteristic of the gas-engine; that its maximum power is reached when the cylinder is full of mixture, and it seriously militates against gas power in the minds of those who install a smaller steam-engine with the deliberate intention of overloading it, a more or less universal custom.

The Gas-Engine Generator: Present practice assigns an overload capacity of 10% sometimes of 15% to the gas-engine. Standard generators are, however, capable of sustaining 25% overload continuously within safe temperature limits. It is, therefore, permissible to rate the generator on a closer margin; that is, give it a higher rating for gas than for steam work. This enables the generator to run normally at a slightly higher efficiency, and reduces the cost of the power unit per kilowatt capacity, which is desirable owing to the high cost of gas-engine construction.

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* Kinetic Efficiency is defined as:

$$\frac{\text{Thermal equivalent of useful output}}{\text{Total heat input in gas.}} = \frac{2\,545}{\text{B.t.u. per B.h.p-hr.}}$$

Load-Factor: The term load-factor is often used in widely different senses, usually as follows:

$a \quad \frac{\text{Average load on engine}}{\text{Rated Capacity.}}$, during operating period only.

$$b \quad \frac{\text{Average load on station}}{\text{Total rated capacity of generators.}}$$

$$c \quad \frac{\text{Average load on station.}}{\text{Maximum (or swinging) maximum.}}$$

$$d \quad \frac{\text{Average load on station}}{\text{Average (or steady) maximum.}} = 100\,\frac{\text{kw-hr. generated}}{\text{Max. kw-hr.}}(\%)$$

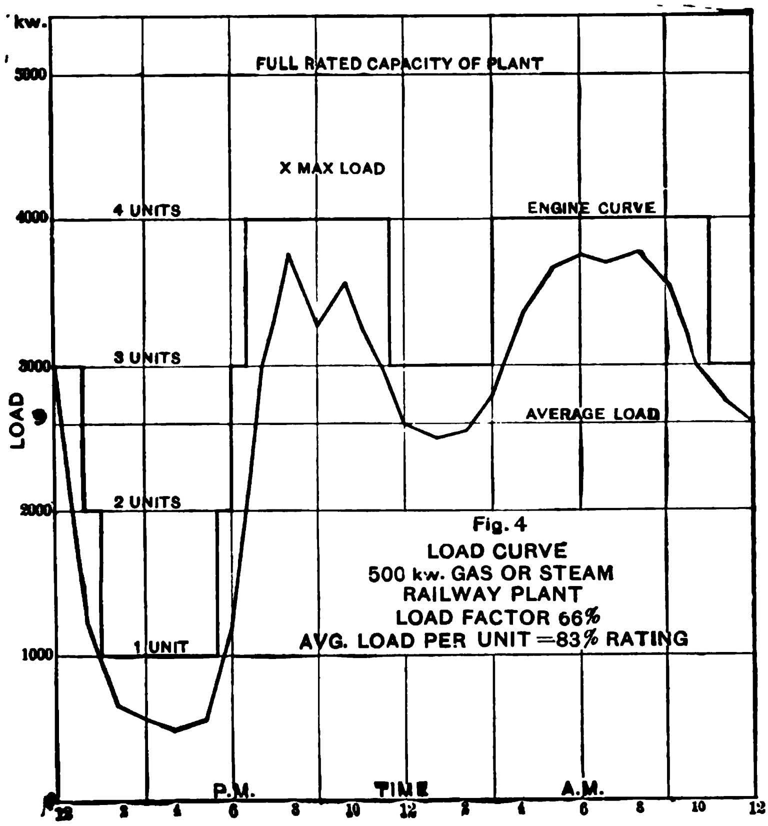

Fig. 4
LOAD CURVE
500 kw. GAS OR STEAM
RAILWAY PLANT
LOAD FACTOR 66%
AVG. LOAD PER UNIT =83% RATING

By average maximum is meant the maximum shown on the station load-curve plotted from wattmeter readings. This last is the true load-factor and, for 24 hours' service, it alone offers an impartial basis for the comparison of station costs and economies; although *b* may be used in comparing the operation of a given plant at different seasons, *a* is of importance in properly proportioning or " blocking in " engine capacity to suit a particular load-curve, such as Fig. 4, with the best ultimate economy. By integrating both the station load curve and the corresponding engine curve the average 24-hr. load per engine can be readily estimated, and the consequent water and coal consumption of the station approximated.

Much emphasis has very properly been placed upon the effect of load-factor on fixed or capital costs. But in a plant with load-factor varying from month to month, as in a central lighting station, the effect on operating costs and economies is fully as pronounced. The accompanying curve, Fig. 5, shows average results from a 750-h.p. plant using producer-gas fuel and subject to a variable load-factor during the various seasons. The curve is practically a hyperbola, as it should be, and within the working range of the plant it shows an increase of from 1.9 to 3 lb. of coal per kilowatt-hour, or 27.5% with a decrease of 60% in load-factor. At normal working the plant uses about two pounds of coal per kilowatt-hour.

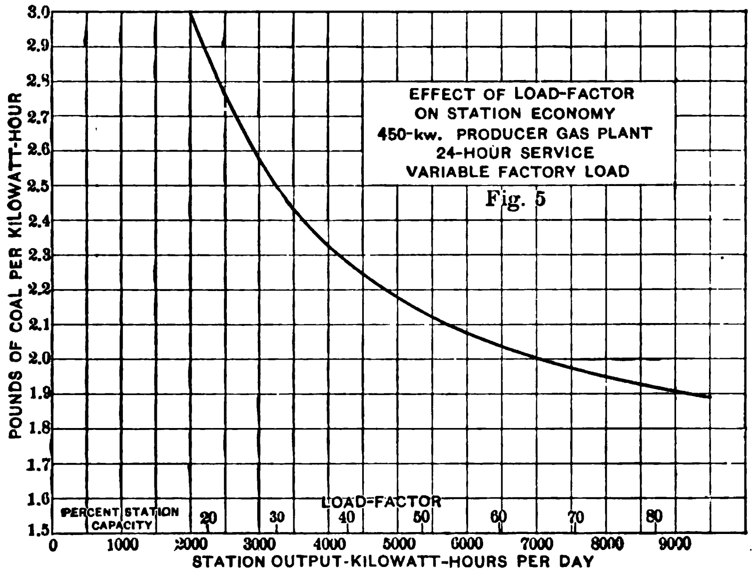

Fig. 5

For a steam plant operating under variable load-factor the general character of the curve is the same. Thus in a 7 500-kw. light and power plant using steam-turbines the operating cost was reduced from 0.5 to 0.325c. per kilowatt-hour or 42.5% of the normal, with an increase of only 13% in load-factor. See Fig. 6.

It is therefore apparent that as two factors combine to give the total cost of power; namely, the operating costs and capital or fixed costs, both should be considered in determining the effect of load-factor . As a matter of fact, one is about as important as the other. With a high load-factor, 50% to 70%, such as occurs in a large railway plant, a small change has a comparatively insignificant effect owing to the flatness of the curve, but in a lighting plant where the load-factor ranges from 15% to 25% the values change with great rapidity. An excellent method of obtaining a clear idea of the total effect of

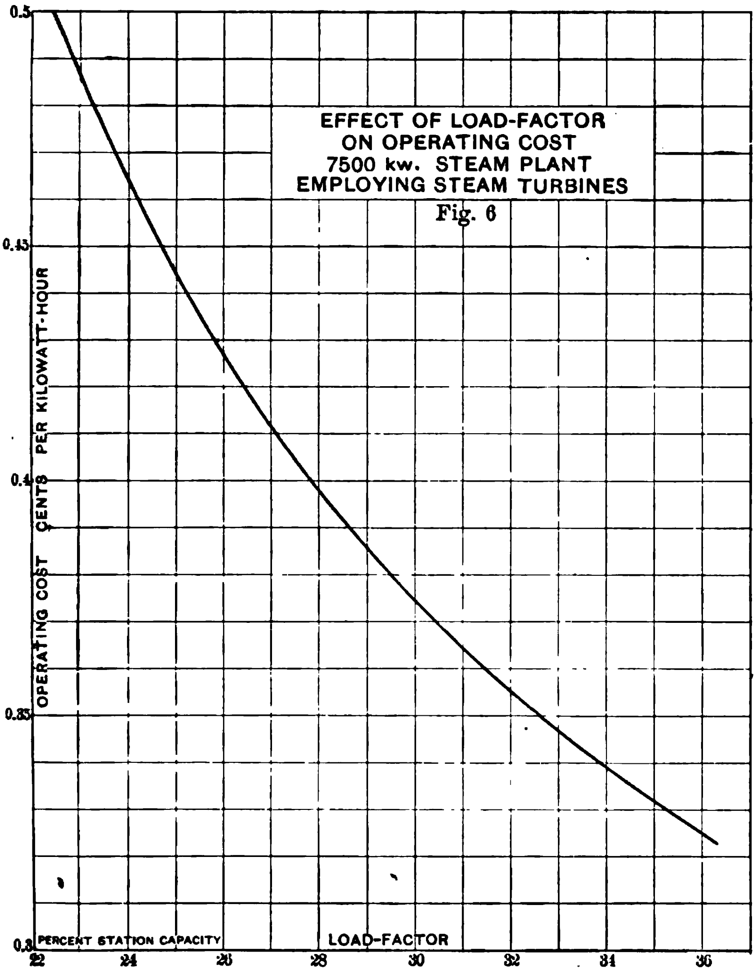

Fig. 6

load-factor is by means of a diagram, Fig. 7, similar to that used by Dr. Mertz, in which capital costs are plotted below, and operating costs above the horizontal axis, the total ordinate giving total costs. The combined effect of the two curves is

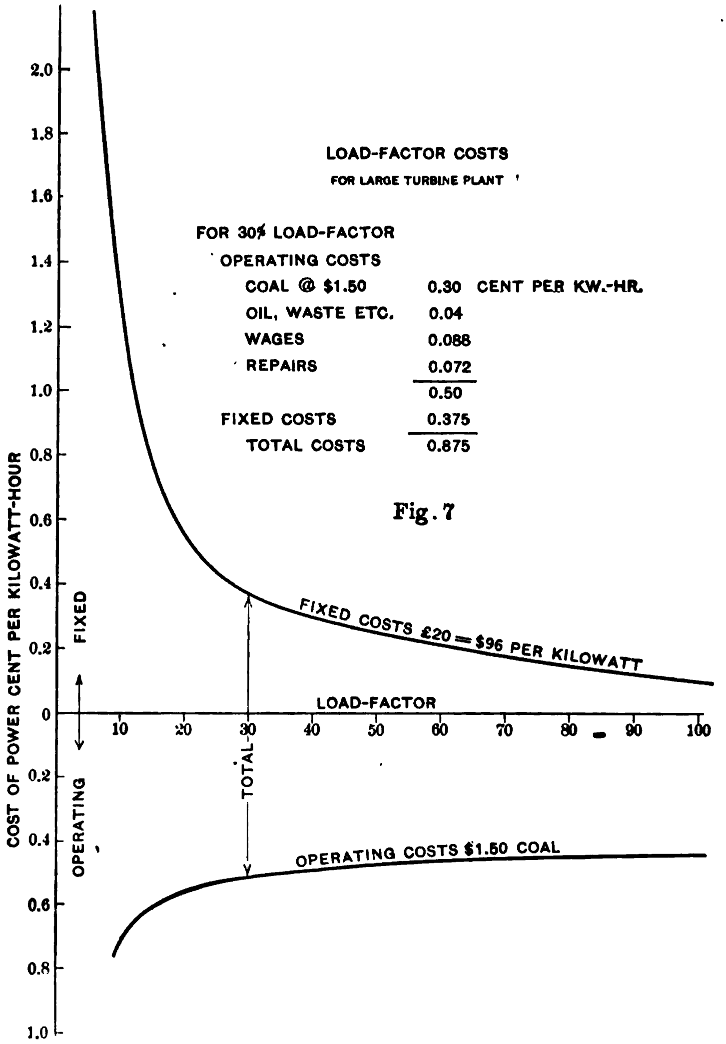

Fig. 7

very striking, and emphasizes the necessity of increasing the average all-day load upon a power station by every legitimate means. Also of restraining as much as possible the capital cost of a power station necessarily operating on low load-factors.

A paper presented at the 203d Meeting of the American Institute of Electrical Engineers, New York, January 26, 1906.

A SELF-EXCITING ALTERNATOR.

BY E. F. ALEXANDERSON.

The large amount of work which has been done on self-exciting alternators and the numerous different types of these alternators that have been proposed clearly indicate the desirability of such a machine. This paper describes a type of self-exciting alternator developed by the author, but in the course of the description the work of other inventors will also be briefly referred to.

The theoretical possibility of a self-exciting alternator was demonstrated years ago, both in this country and in Europe, but insufficient knowledge of the principles underlying commutation and voltage regulation led to the early experimental machines being abandoned as unsatisfactory. The real reason for the unsatisfactory behavior of these machines was apparently not fully understood at that time, with the result that the rectifying commutator then used was condemned as being unfitted for supplying the field excitation for self-exciting alternators.

Inventors that have worked on this problem in later years have employed entirely different methods. Heyland's self-exciting alternator, often mentioned in recent technical literature, has been developed from the principle of a direct-current armature with a multi-segment commutator and a number of coils connected to the segments. The mechanical construction of the direct-current armature is unsuitable when applied to the field of an alternating-current generator, and for this reason the later machines of the Heyland type are constructed with projecting poles in a manner similar to the poles of ordinary generators. In Heyland's generators good commutation is obtained by dividing the field winding into a sufficient number of circuits interconnected in such a way as to reduce the reactive voltage when the current is commuted from one field circuit to another. The commutation is further improved by a set of revolving resistances shunting the commutator segments.

Another type of self-exciting alternator has been devised by Latour.* This employs a multi-segment commutator, and a field winding with a number of coils in which the current is successively changed as the brushes pass the commutator segments.

The self-exciting alternator designed by the author does not use the multi-circuit arrangement of the field, but can be considered as a development from the old principle of rectifying commutator, cited in reference to the early experiments. A novel feature of this machine is the automatic voltage regulation accomplished by a special application of the field rheostat. While in ordinary generators the field current is controlled by hand regulation, this machine employs a three-phase field rheostat in which the voltage drop is automatically cut down to the desired extent by a three-phase current forced through the rheostat in opposite direction to the field currents. The current used for reducing the drop in the rheostat is taken from a transformer connected in series with the armature circuit. In this way the field current is regulated with respect to the power-factor as well as to the amount of current taken from the generator.

The principles which must be borne in mind in the design of self-exciting compounded alternators are:

A. The commutation must be satisfactory with a load of any character, without shifting the brushes.

B. The compounding must be arranged so that armature reaction is compensated for, not only with variations of the load, but also for changes in power-factor.

It will be shown that both of these conditions can be obtained without departing from the simplicity of a single field winding of the ordinary type which carries a direct current and is fed from two terminals connected to a rectifying commutator. Any standard type of field winding as at present applied to the ordinary type of alternating-current machinery can therefore be used with this system.

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* The question of priority between Latour and Heyland, who developed their machines independently, is a matter which falls outside the scope and purpose of this paper.

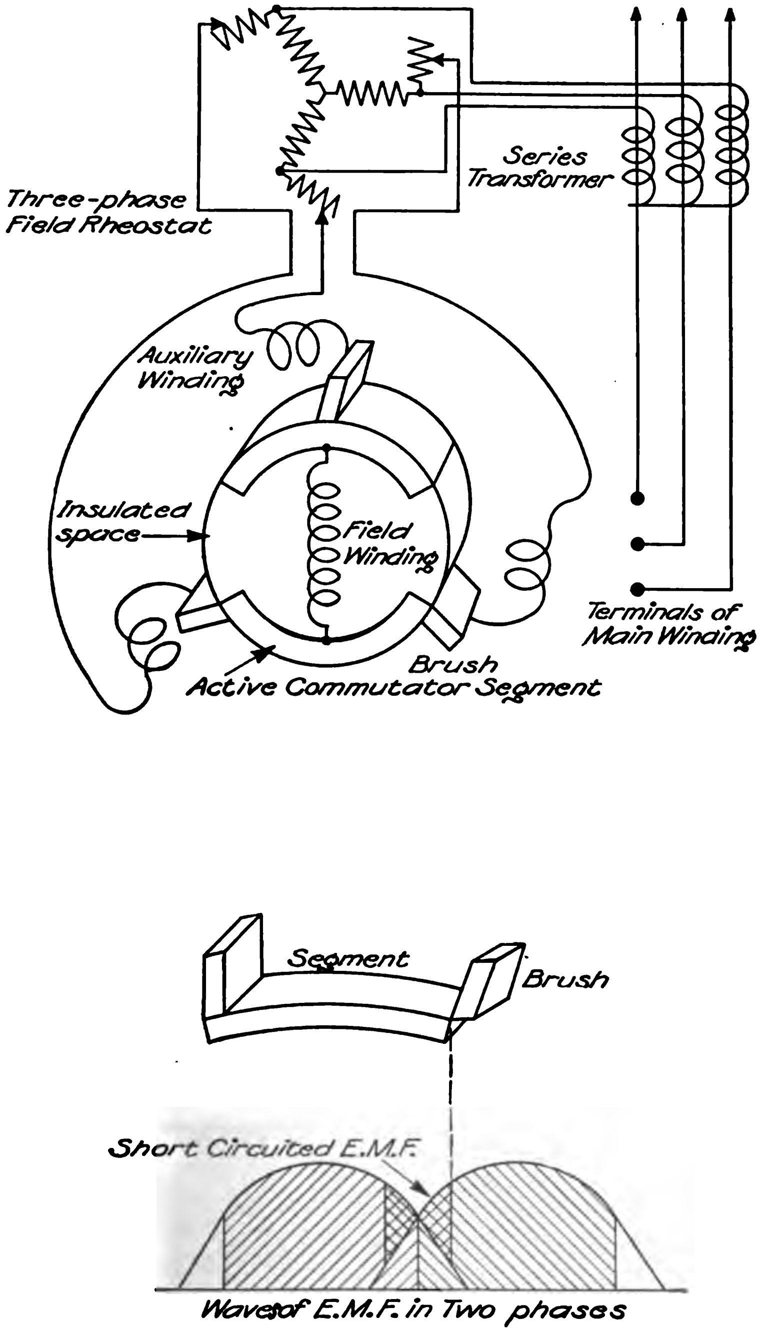

Three-phase
Field Rheostat
Series
Transformer
Auxiliary
Winding
Insulated
space
Field
Winding
Brush
Active Commutator Segment
Terminals of
Main Winding
Segment
Brush
Short Circuited E.M.F.
Waves of E.M.F. in Two phases

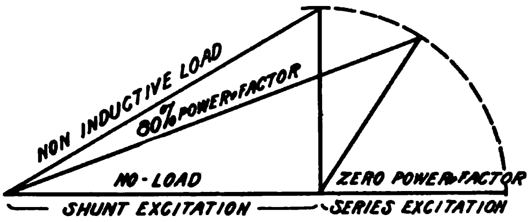
FIG. 1.

A general diagram of the author's type of alternator is shown in Fig. 1. The exciting current is generated in an auxiliary three-phase winding placed in the same slots as the main armature winding. The terminals of this auxiliary winding are connected to three sets of brushes that bear on a rectifying commutator of special type. This commutator has one active segment per pole, covering practically two-thirds of the pole-pitch, the remaining one-third of the arc being insulated. Each alternate segment is connected to one terminal of the field winding, and the remaining segments to the other. By this arrangement it is possible to make the commutation independent of the reactance which is inherent in the ordinary type of field winding, and the whole process of commutation is carried out in the stationary circuits before the current enters the field.

The voltage generated in the auxiliary winding is sufficient to supply current for excitation at full inductive load; and the excitation is adjusted to the proper no-load value by a three-phase rheostat inserted in the neutral point of the auxiliary winding. Automatic compounding is accomplished by means of a series transformer connected to the rheostat; the transformer sends a current through the rheostat in a direction opposite to the field current, thereby eliminating the voltage drop in the rheostat. The elimination of the voltage drop in the rheostat changes over more or less of the field current from the rheostat to the series transformer. The secondary current of the series transformer is in phase with the line current, while the field current is practically in phase with the voltage. The amount of boosting in the field circuit will therefore depend not only upon the value of the secondary current, but also upon the power-factor of the load. A function of the rheostat which is just as important as the field control, is its influence on the commutation. This will be explained later. As far as commutation is concerned, the full resistance of the rheostat may be considered as always being in circuit, although the larger part of the field current may flow through the series transformer.

As the phenomenon of commutation with this kind of rectifying commutator is entirely different from that with the ordinary multi-segment commutator of a direct-current machine, it may be of interest to enter somewhat further into the theory of commutation in the new type of alternator. In order to understand the operation of the commutator it must be borne in mind that the field winding carries a continuous current in spite of the fact that the impressed voltage is of a pulsating character. The only fluctuation that can occur is the quite negligible pulsation needed to induce a voltage large enough to overcome the ohmic resistance of the winding. The current in the three-phases of the exciting circuit is not an alternating current of the regular sine-wave shape, but is formed of pieces, so to say, cut off from the direct current. The commutation consists in changing over the direct current from one phase of the exciting circuits to another, and occurs when one brush has come in contact with a segment and another brush is ready to leave the same segment and run into the dead part of the commutator. At this instant the current must be changed, in the brush which enters the segment, from zero to full value of the direct current; and the current in the other brush must be reduced from maximum to zero. Commutation should occur a little later than at the moment in which the induced voltages are equal in the two phases undergoing commutation. If we imagine that one of the brushes is leaving the segment when the voltages are exactly equal, that brush would yet be carrying a part of the field current and this current would suddenly be interrupted and changed over to the other circuit. If the stationary circuit has a high reactance the sudden change of the current would induce a voltage between the brush and the segment, and thereby cause a spark. The moment of commutation should, therefore, be delayed to such an extent that the difference in voltage between the two phases begins to force a cross current through the completed circuit formed by the two phases and the rheostat. As soon as the two brushes are in contact with the same segment they naturally divide the field current; but the cross current which is superimposed on the field current will weaken the current in one of the phases and strengthen it in the other phase. If, therefore, the cross current is half as large as the field current at the moment of rupture, one of the phases will carry the entire current and none will pass through the brush which is leaving the segment. In this way complete commutation takes place just before the brush leaves the segment, and consequently no sparking will occur. The time which is required for the cross current to reach the value of one-half of the field current depends upon the reactance and resistance in the external stationary circuit.

From the preceding it is evident that whatever be the values


NON INDUCTIVE LOAD
80% POWER FACTOR
NO-LOAD
ZERO POWER FACTOR
SHUNT EXCITATION
SERIES EXCITATION

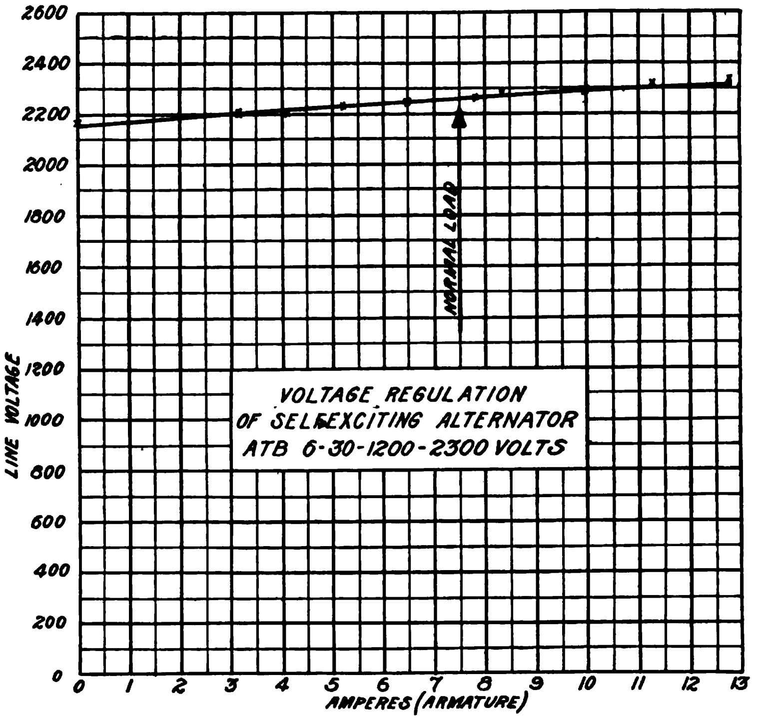

VOLTAGE REGULATION
OF SELF-EXCITING ALTERNATOR
ATB 6-30-1200-2300 VOLTS
NORMAL LOAD
LINE VOLTAGE
AMPERES (ARMATURE)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13

FIG. 2.

of these quantities, a position can be found for the brushes where commutation will occur without sparking. But it is also evident that a slight variation in the position of the brushes may cause severe sparking if the circuits are not properly designed. If the circuits consist of a winding with a very small resistance and high reactance, a small difference in voltage will cause a large cross current to flow between the two phases, and this cross current cannot be broken suddenly without sparking. In order to obtain successful operation of the commutator, the generating circuit should be designed with as little reactance as possible and with a considerable amount of resistance.

Since this machine has been developed the question has often been asked, why a rectifying commutator has been so successful on this particular application, while it cannot be used for direct-current generators. One reason for its success when used for field excitation is that the presence of the rheostat in the stationary exciting circuit introduces a resistance which prevents the flow of an excessive current when two brushes are in contact with the same segment. A rheostat is used in the field circuit of any generator; and although it consumes a considerable part of the exciter voltage it is not objectionable, on account of the small power involved. Another reason for the success of the rectifying commutator when applied to field excitation is that the field current is generated by a magnetic flux large enough for the total output of the machine, permitting the auxiliary winding to be designed with a small number of turns and low reactance.

The effect of each of the different conditions which influence commutation has been determined experimentally. The most important of these conditions are:

1. Effective voltage across the brushes.
2. Effective voltage of the auxiliary winding.
3. Resistance of the stationary exciting circuit.
4. Reactance of the stationary exciting circuit.
5. Current density in brushes.
6. Velocity of commutator.
7. Amount of direct current taken from commutator.

The above quantities simply affect commutation in determining the extent to which the brushes may be shifted without causing sparking. The method of investigating how these several factors influence commutation has been to vary one quantity at a time, keeping all the others constant. In general the results show that the range over which the brushes may be shifted without sparking is inversely proportional to the voltage across the brushes and, up to a certain limit, almost directly proportional to the resistance in the stationary exciting circuit. It is also an interesting fact that commutation is independent of the current taken from the commutator, if the voltage of the auxiliary winding and the resistance of the rheostat are kept constant.

In order to insure successful operation of the commutator in a compounded machine it is not only necessary to study the phenomena of commutation independently, but several other factors should also be taken into account. A machine should be designed so that the most favorable position of the brushes varies as little as possible for different characters of load. In order to understand this it will be necessary to enter somewhat further into the theory of compounding; but in passing it may be mentioned that it has been demonstrated that a machine can be designed with the most favorable position of the brushes coincident for no load and for full load.

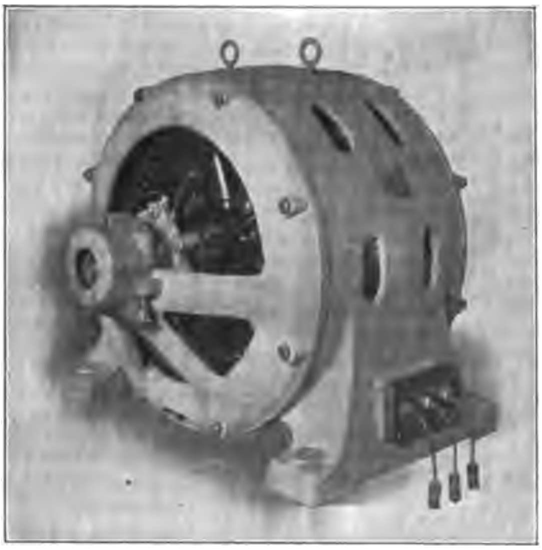


FIG. 3.—100-kw. Self-exciting Alternator.

In considering the theory of compounding self-exciting alternators it will be assumed that the rule suggested by the American Institute of Electrical Engineers, and generally accepted in calculating the regulation, is true, as it is found to agree with practice in the majority of cases. According to this rule, the excitation which is needed to maintain a certain voltage at the machine terminals, neglecting the ohmic drop in the armature winding, can be found by combining the ampere-turns of the no-load excitation with the ampere-turns of the synchronous impedance at right angles for non-inductive load; and for any other load at an angle which corresponds to the power-factor. The phases of the auxiliary winding are connected in such a manner that the voltage induced in them lags by 90 electrical degrees behind the corresponding phases of the main winding. The secondary circuits of the series transformer are closed through the rheostat, and the current combines with the field current at right angles at non-inductive load, but is in phase with it at zero power-factor. At full inductive load of zero power-factor the field current in the rheostat is completely neutralized by the current of the series transformer. The effect of the series transformer on the exciting circuit is, therefore, equivalent to an additional electromotive force which can be combined with the electromotive force of the auxiliary winding at an angle dependent upon the power-factor. The resulting electromotive force available through this arrangement, for excitation, is obviously the same as that calculated by the A. I. E. E. rule.

The quantities have to be slightly modified in practice to produce the exact degree of compounding or over-compounding desired. The compounding for non-inductive load can be changed at will without changing the compounding for load of zero power-factor. This is accomplished by so connecting the armature that the electromotive force of the auxiliary winding lags less than 90 degrees behind the electromotive force of the main winding. If the effect of the series transformer is considered as an electromotive force combined with that of the auxiliary winding, at approximately right angles for non-inductive load, it is evident that the resulting voltage impressed on the brushes has not the same phase relation to the voltages of the machine at full load as it has at no load. In order to insure good commutation at any load, it is desirable that the three-phase voltage impressed on the brushes should pass through its zero point at a given position of the commutator.

In every alternating-current generator the armature reaction for non-inductive load is a magnetomotive force tending to produce a set of poles midway between the poles excited by the field winding. The magnetic field of a loaded generator is, therefore, not the same as the field at no load; it is a combination of the magnetic flux induced by the field winding and that generated by the armature reaction. The angle of displacement between the resulting field and the mechanical center-line of the poles depends upon the design of the magnetic structure, and varies widely in different types of machines. The simplest case to illustrate is a field of the high-speed turbine type in which the field winding is placed in slots, as this type offers uniform reluctance to the lines of force in all directions. The field excitation and the magnetic flux induced by the armature reaction are, therefore, proportional to the corresponding magnetomotive forces, and combine at right angles for load of unity power-factor. When the machine is under load the resulting field is displaced from the mechanical center-line of the poles by an angle; the tangent of this angle is the armature reaction divided by the field excitation. From this it will be seen that it is possible to design a self-exciting compounded machine so that the most favorable position of the brushes remains practically constant. If the compounding is calculated according to the A. I. E. E. rule, the voltage of the compounding should have a relation to the voltage of the auxiliary winding approximately the same as the armature

FIG. 4.—Revolving Field of 100-kw Self-exciting Alternator.

reaction to the field excitation. On account of the armature reaction the resulting field will lag a certain angle behind the center line of the poles; the electromotive force, however, induced by the field in the auxiliary winding is so combined with the electromotive force of the compounding that the resulting voltage is ahead of the machine voltage by approximately the same angle as the field is distorted by the armature reaction.

The accompanying oscillograms, Figs. 8 and 9, show the shape of the current wave in one of the phases of the exciting circuit, and confirm the theory of commutation given above. One of the diagrams was taken at that position of the brushes which is most favorable for commutation. The top of the wave is a straight line; or in other words, a direct current, as should be expected. After this comes a period of commutation. The current is gradually brought down to zero through the effect of the cross current, and remains zero until the brush comes in contact with the next segment. The other diagram was taken with the brushes shifted a certain distance from the most favorable position. The peak at the beginning of the current wave indicates that the cross current had reached too large a value before the circuit was broken. Even under these conditions, however, commutation occurred without sparking.

The fact that all the phenomena of compounding take place within the magnetic circuit of the field makes the compensation for the armature reaction instantaneous. In any generator a sudden increase in the armature reaction produces, by induction, a momentary increase of current in the field winding; in the present case this increase of field current is maintained by the increased voltage at the field terminals, which, because of the compounding, varies simultaneously with the change of load. This fact can be demonstrated by observing an incandescent lamp fed from the alternator circuit. If the generator runs at no load, and full load is switched on, no fluctuation whatever can be observed in the brightness of the lamp.

The compounding for non-inductive loads affords an easy method of compensating for speed variations in the prime mover, which are due to fluctuations of the load. This method of compensating for the speed variation is appreciated in the case of direct-current generators, although the compensation is not so good as in alternating-current machines. The latter machines have a compounding characteristic which gives a perfectly straight line, as shown in Fig. 2; whereas the well-known shape of the compounding characteristic of the direct-current generators usually shows a much larger increase of voltage at three-quarters' load than at full load.

The illustrations in Figs. 3 to 7, inclusive, show some of the features which have been adopted in the type of self-exciting alternators developed by the author. The commutator is built on a straight shell, and the segments are held together by two steel rings shrunk on the ends of the bars. These rings serve as an electrical connection between the different segments, one of the rings being connected to every other segment, and the other ring to the rest of the segments. The two terminals of the field winding are connected to two segments of opposite polarity, and consequently to the respective end-rings. In this way the end-rings can be used at any time as collector rings for separate excitation. The spaces between the segments are electrically equivalent to air-gaps, but in order to support the brush mechanically the dead spaces are filled with a number of small copper bars separated by mica insulation.

FIG. 5.—Armature with Auxiliary Winding.

In parallel operation with ordinary machines, and also with other self-exciting machines, these alternators have given favorable results. When two or more over-compounded alternators are operated in parallel, in the same station, the series transformers should be interconnected by an equalizer bus-bar

Fig. 6.—500-kw. Self-exciting Turbo-Alternator.

in the same way as the series fields are equalized in compounded direct-current generators. If the self-exciting alternator is to run in parallel with a separately-excited generator, the compounding should be adjusted to correspond to the inherent regulation of the separately-excited machine, in order to divide the current properly. When considering the parallel operation of these machines, special attention may be called to a convenient method which can be adopted for synchronizing. If one generator is to be started and synchronized with other self-exciting generators, it is only necessary to bring the machine up to approximate synchronous speed as held by the governor, and to close the main switch. The closing of the switch will cause a momentary rush of current, but the compounding of the other generators will prevent any material disturbance of the line voltage; and the machine, which has been started, will build up its field immediately. The rush of current which occurs when closing the main switch, if the generators are out of phase, is, however, not nearly so great with self-excited as with separately-excited alternators. In the case of the separately-excited machine, a north pole takes the position which should be occupied by a south pole, causing a cross current to flow, which is twice as large as a short circuit on the generator; whereas the self-excited machine has no definite polarity before synchronization, and the auxiliary winding tends at every moment to generate a polarity corresponding to the line voltage. This phenomenon can be observed if a polarized direct-current ammeter is connected in series with the field circuit during synchronization. The ammeter needle will swing on both sides of the zero point with decreasing speed and

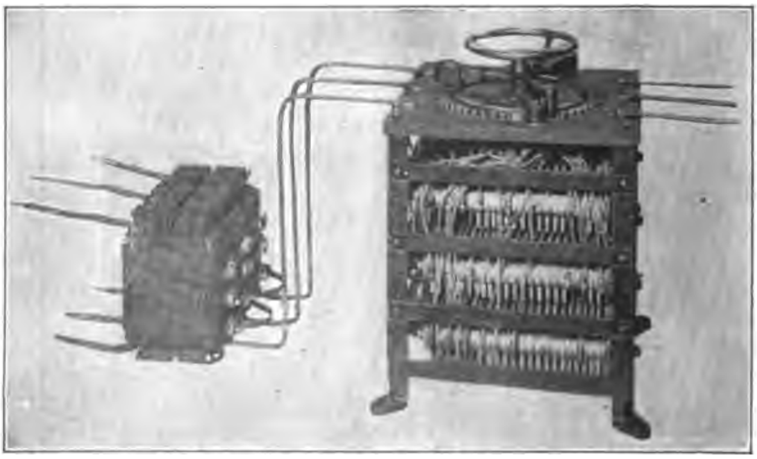


FIG. 7.—Series Transformer and Rheostat for 500-kw. Self-exciting Alternator.

increasing amplitude, until it finally stops either on the positive or the negative side.

If the self-excited machine is allowed to build up its own voltage independently, and is synchronized in the ordinary way, there is less chance of failure than with a separately-excited generator. The following experiment was made: A 500-kw. self-excited generator was switched in with a 500-kw. separately-excited machine when directly in opposition to the latter. The self-excited machine immediately changed its polarity, only an instantaneous spark being noticed at the commutator.

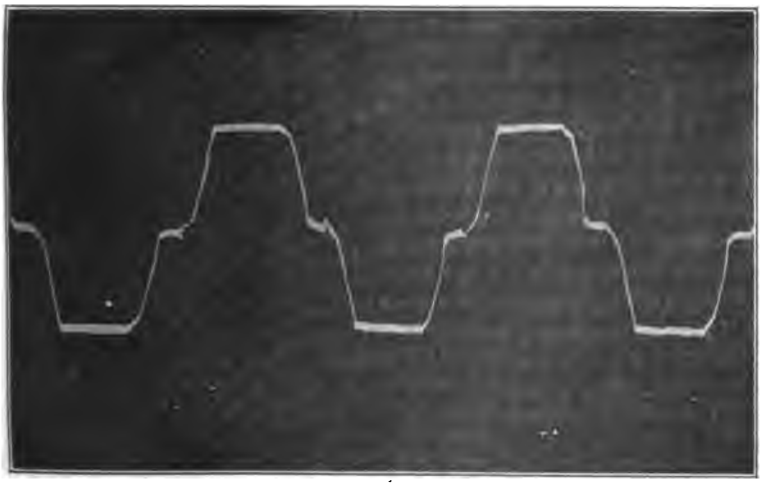


Fig. 8.—Oscillogram of Current in Brushes.

Tests which have been made give promise of an extensive use of self-exciting machines as synchronous motors. A self-exciting synchronous motor can be either shunt connected or compounded. Compounded synchronous motors will be found to be especially useful for boosting the voltage at the ends of long transmission lines. In this case the series transformer which is used for compounding should be connected in series with the main line, so that an increase of current in the rest of the system raises the excitation, with a consequent increase of leading current in the synchronous motor.

The method of starting a self-exciting synchronous motor is the same as that of starting an ordinary synchronous motor until the speed approaches synchronism. The ordinary synchronous motor is an induction motor brought up to an approximately synchronous speed through the inductive relation of stator and rotor windings. When the field is excited the revolving part receives alternately positive and negative impulses as the poles slip over the synchronous positions, until one positive impulse is strong enough to pull the machine into step. In synchronizing the self-excited synchronous motor, the same phenomena will occur as in the self-excited generators. When the torque due to inductive effect begins to decrease on account of the decrease of slip the excitation impressed through the commutator becomes active, and the field will receive a series of impulses—all in the same direction—which increase in strength with the decrease of slip until synchronism has been reached.

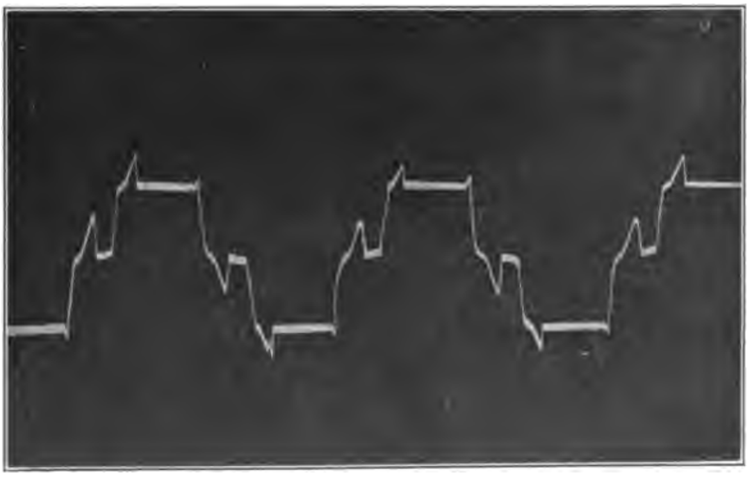


FIG. 9.—Oscillogram of Current in a Brush at an Unfavorable Brush-shift.

It is anticipated that the self-exciting alternator will be extensively used on account of its automatic features, and the cheaper and more simplified station arrangements that it renders possible, especially in steam-turbine installations where direct-connected exciters are not desirable. The abolishing of the exciter plant with its steam piping, engine, and motor-generator set, will considerably simplify the station. The saving of labor may also be considerable, as the attendants will have only the main generating units to operate. The saving in cost and labor on account of the simplified arrangement applies to large as well as to small stations; and it is probable that self-excited alternators will be preferred to separately-excited alternators for the same reasons that self-excited direct-current machines are generally preferred to those that are separately-excited.

Any ordinary type of alternating-current generator can be adapted for the system of excitation and compounding described, and the experience already gained clearly indicates that it is applicable to large as well as to small units. The fact that the machines described have passed the experimental stage, and that one of the leading electric concerns is manufacturing them as standard apparatus, gives promise that more data regarding the practical and commercial operation will soon be available.

DISCUSSION ON "A SELF-EXCITING ALTERNATOR," AT NEW YORK, JANUARY 26, 1906.

A. E. Kennelly: This paper is, I think, extremely interesting, because of the apparent simplicity of the means that have been adopted, not only for the exciting, but also for the compounding of the alternator described. The first dynamo machines were, of course, separately excited, and it was considered a great step to make them compounding. When alternators came into use, it was considered much more difficult to make them self-exciting, on account of the direct current required by the field, the armature producing alternating current. Self-exciting was considered more important for them than compounding, because in the case of alternators it was not the IR drop that had to be compounded, but the IZ drop; a two-dimension problem instead of a one-dimension problem, and therefore more difficult as the square, so to speak.

In the past, various methods have been used for compounding alternators, but these reached only partial success in practice, and have not been regarded as available for high-voltage machines. Here, however, seems to be a means for alternator compounding applicable to machines of any voltage and on any load. In fact it looks as if a station fitted with such machines as these—if they work out satisfactorily in practice—might have no machines but the main turbo-generators, no auxiliaries for driving exciters, and no synchronizers; so that the station operator would just close the alternator switch when he so desired, and throw any machine on as soon as it came up to speed. If this is really more than a dream, something to be hoped for in the near future, I think it is a result upon which not only the author of the paper, but the entire INSTITUTE, may be congratulated.

C. F. Scott: The self-exciting of alternators is so interesting and involves so many features that one can scarcely do justice to it without more careful consideration than has been possible this evening.

The method that has been described this evening certainly overcomes a great many of the difficulties encountered in early alternator design; this method is ingenious, and it possesses characteristics that apparently render it superior to many other methods which have been proposed for accomplishing the same results.

An objection to this method of exciting and compounding is that the alternator is quite sensitive because it is self-exciting, and variations in the general voltage, particularly variations in speed, are immediately transmitted to the exciter. In plants driven by water-wheels the speed is subject to considerable variation; in a case like this the voltage regulation is apt to be more nearly constant if the exciting voltage is obtained from an independent source. If the load is heavy and the speed drops there is especial need for exciting current, whereas under these conditions the self-exciting machine is apt to have a falling off in field current. On the other hand, when the load is thrown off and the speed rises, either because the governor is sluggish, or fails to act at all, the voltage will rise very considerably, as the field current increases with the speed. This characteristic is inherent in all self-exciting machines.

The field of a direct-current generator is usually much more highly saturated than is the field of an alternator, consequently the alternator is much more sensitive to variations. Sometimes the exciter is driven either directly or indirectly from the main alternator, so that the speed of the exciter is subject to the variations in the speed of the main alternator. Even this has not been satisfactory in some cases of widely fluctuating load, and a separately-driven exciter at constant speed has been found an acceptable remedy for avoiding the previous variations in voltage. I am of the opinion, therefore, that self-excitation is not, to say the least, a complete and universal solution of the problem of excitation of alternators.

W. L. R. Emmet: I have seen this device working under very trying conditions, and its performance was astonishingly good. It is the quickness of its action that is astonishing. I have seen a machine of this kind suddenly thrown on heavy inductive loads of more than full-load capacity, without a sign of sparking on the commutator, or appreciable flickering in the lamps. The nature of the device is such that it is capable of application to any size machine, because it can be arranged in multiple circuits, with no more current in any one circuit than that used on small machines. Experience indicates there is almost no limit to the application of the idea. I think the final results are chiefly due to the care with which Mr. Alexanderson has worked out the proportioning of everything concerning it.

As to the variations of speed, that is a limitation in all self-exciters; at the same time, if this device is employed it can be compounded for speed as well as for load, as most machines are governed by load; a machine with this device is capable of doing this particularly well.

A. S. McAllister: The phase position of the voltage generated in the auxiliary winding depends on the mechanical position of the winding on the core, and the phase position of the voltage in the series transformers depends upon the power-factor of the load. At non-inductive load these voltages add at a certain angle, and at inductive load they add at a different angle. A change in the angle is equivalent to a change in the position of the brushes, and I would ask if this change has any effect on the commutation when the load is varied from its full inductive to its full non-inductive value without moving the brushes?

E. F. Alexanderson: The difficulty is apparently to make the machine commutate properly for no load and non-inductive load, because the voltage impressed on the commutator is not of the same phase relation to the machine voltage at no load and full load. The field is, however, distorted by the armature reaction at the same time as the voltage impressed on the commutator is shifted ahead of the electromotive force of the auxiliary winding. Therefore the position of the brushes at no load is nearly the best position for non-inductive load. At inductive load the voltage of the series transformer combines with the voltage of the auxiliary winding in a straight line, and at the same time the armature reaction combines with the field excitation in a straight line, and there is no reason whatever for any displacement.

A paper presented at the 204th Meeting of the
American Institute of Electrical Engineers
New York, February 28, 1906.

TELEPHONE ENGINEERING.

BY J. J. CARTY.

Engineering may broadly be divided into two classes, civil and military. Military engineering is that which pertains to the conduct of war and is sufficiently understood to require no description. Civil engineering, as I am now using the term, comprehends all forms of engineering which are conducted without special reference to the operations of war. Falling within this definition of civil engineering we have electrical engineering, mechanical engineering, telegraph engineering, telephone engineering, and some others. As taught in colleges, however, and as generally understood, civil engineering is restricted and deals more especially with that branch of the art which pertains to the construction of bridges, water works, railroads, harbor improvements, and other public works of like character.

Inasmuch as the telephone is an electrical instrument, and inasmuch as electrical phenomena exert a dominating influence in the telephone art, telephone engineering is classed as a branch of electrical engineering, although it will be shown as I proceed that telephone engineering comprehends important elements not at all electrical in their character; indeed, it is a recognition of the existence of these elements, and a knowledge of how to deal with them adequately, that constitutes one of the important requirements of telephone engineering. A good knowledge of electrical laws and a fair acquaintance with electrical machinery may be gained in our electrical schools; and graduates from them are, as a rule, proficient in these matters.

Telephone engineering comprehends not only these, but other factors, the existence of which is not generally recognized. In this paper I shall, owing to the limitations of the time at my disposal to-night, attempt to explain the nature of only some of these factors, indicating their most important bearing upon the general subject. From your own knowledge you will be able to supply many more instances, illustrating perhaps better than those which I have chosen, the ideas which I wish to make plain.

To describe the proper scope of telephone engineering in its relation to the telephone industry is to consider the functions of the telephone engineer. Not so many years ago it was thought that the functions of the telephone engineer consisted of doing little more than to provide and install switchboards. He was supposed to be consulted occasionally about the station apparatus, and later, when cables were introduced, his activities were extended so as to include the testing of cable after it had been bought and laid.

At the time of which I speak, telephone companies took almost an exclusively switchboard view of the telephone business. A building would be selected by someone connected with the company, and the engineer would be consulted principally as to the type of switchboard and the placing of it in position. The size and location of the building, its relation to the existing and probable future subscribers, and all of the vast number of other factors now considered so vital in determining such matters, received but scant consideration. So it was with cables; whether the cable should contain wires of No. 22, No. 19, or No. 16 gauge; whether the insulation should be of cotton, rubber, or gutta percha—these were questions which were as likely to be settled by the purchasing agent as by the engineer.

To one acquainted with the conditions of those times this is not at all surprising, because the telephone engineer of that period shared with all of the rest of the world the then prevailing ignorance concerning matters which have since been proved by laborious investigations to be governed by well established laws, the nature of which was then unknown.

The proper status of telephone engineering and the true scope of the telephone engineer differ as greatly from this primitive view as does the modern telephone system differ from that which obtained in the period about which I have just spoken.

I shall endeavor to give a correct view of the true scope of telephone engineering and to do so I shall broadly discuss a typical problem in telephone management, illustrating the various points I wish to make by reference to certain details which will be considered in connection with the problem chosen.

Let us take the case of New York City, with the suburban territory tributary to it, and assume that it is the intention of the telephone company to install within that territory a telephone system which will work at a proper degree of efficiency and at the same time yield to the investor a fair return upon his investment; and that it is necessary not only that this condition should exist during the first stages of the project, but that the undertaking should be so managed that this condition will be maintained indefinitely. With such a problem before the telephone management, what part of it should the telephone engineer be required to work out? I shall answer this question by describing in general terms, and sometimes, for the purposes of illustration, in considerable detail, what should be the work of the telephone engineer, in such a case.

The first question which the engineer must decide is, what is the period for which such construction as may be required should be planned? This is a question of far-reaching importance and requires for its answer that a vast amount of data should be collected, and that careful and long-continued study and investigation should be given to a large number of factors. Among the things to be studied and investigated are: first cost and character of construction of the diverse portions of a plant of such complicated nature; annual charges, such as maintenance, depreciation, and interest; and local conditions bearing upon the possibility of the renewal or extension at some future time of all of the elements of the plant.

In addition to this, due regard must be paid to possible changes in the art and also to the fact that, owing to the exigencies of the business, many cases arise where it is necessary to carry out at the beginning, especially in underground work, all of the construction which may ever be needed.

At the outset the question of the period for which to plan depends upon the expectations of growth. With a given expectation of growth, the engineer, by taking into account all of the factors of the case, and balancing the annual charges resulting from the initial investment against the cost of reconstruction and rearrangement of the plant at some future time, arrives at the economical period for which to plan.

In this work the predictions as to growth are of the first importance and, inasmuch as accurate predictions of this kind are attended with the greatest difficulty, it is essential that not only the judgment of the engineer, but that of the business management, and all others who might be able to advise in connection with the matter, should be obtained.

At this stage of the work it is of the utmost importance that the bearing of these estimates of growth upon the future of the plant should be thoroughly understood by the business management, whose functions, in the nature of the case, exercise such a profound effect upon the extent and character of such growth. It is the duty of the engineer to make this point clear and to obtain from the business management serious and responsible estimates of future growth.

The number of lines which may be expected having been agreed upon, the question of for how long a period ahead we should plan is determined by a number of circumstances. For such conditions as obtain at New York, the period for much of the construction has been found to be from 17 to 20 years. This figure is arrived at by taking into account a large number of factors, such as: the life of the central-office switchboard, which is placed at about 15 years; the relative costs of placing in the subways a large number of ducts initially as compared with adding new ducts after a period of about 20 years; the uncertainty regarding the changes in the state of the art; and the difficulty of foretelling with sufficient detail conditions which are expected to obtain during a period so far ahead as 20 years.

In the case chosen for illustration, which was New York, the economical period was found to be about 20 years, and it was attempted to plan for conditions which would obtain in the year 1920 and for each year up to that date. The total number of lines to be provided for in the island of Manhattan is 300 000.* The working out of the general plans for providing for this number of lines, which it was expected would be reached by the year 1920, constitutes what is known as the " 300 000-line study." To give an idea of the nature of part of the work of the telephone engineer, I shall outline in general terms the character of this study.

Having determined upon 300 000 lines as the proper foundation of the study, and having received the proper authorization

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*This figure was substantially modified as the study progressed.

from the business management to proceed on that basis, the next step is to plot on a map the probable distribution of these lines. This is done, not by giving the location of each line, but by indicating by blocks the most probable distribution. Here again the judgment of the engineer must be assisted and directed by the business management, for next in importance to determining the total number of lines to be provided for comes the question of their distribution.

The number and distribution of lines having been agreed upon, the next step is to determine the number and arrangement of central-office districts, the size and boundaries of these districts and the size and location of the central-office switchboards.

It is conceivable, although obviously impracticable, that all of the 300 000 lines might be extended to one central office and operated in switchboards there; it is only necessary to state such a proposition to exclude it from further consideration. On the other hand, it is conceivable that a central office might be established in each block; this also is absurd and needs no further consideration. Somewhere between these two extremes must lie the most economical size and number of central offices. The next stage in the problem is to determine this number; to do this no formula, simple or otherwise, is available. The only practicable method is to lay out the territory to be served, in accordance with a number of different arrangements of districts and centres, starting in, say, with 10 centres and extending the study up to as many as 30 or 40, or even more. In the case of all these arrangements there would be certain elements of cost which would not be changed by the different arrangements of central offices assumed. Block wiring and station instruments are examples of these. These elements of cost are omitted from the comparison. All of the items of cost, however, which vary with the different number and arrangement of central offices, are computed, all of these being reduced to annual charges.

From these figures, as applied to the various layouts, the number of central offices and the districts which are ideally most economical may be seen. I say ideally most economical for the reason that the practical application of such results requires that a difficult and very complicated adjustment of the existing plant, to conform as nearly as possible to the ideal condition, must be carried out.

While it must appear, even from the brief statement of the steps of the study thus far described, that a vast amount of labor and computation are involved, it by no means represents all that must be done. Before there can be made a comparison of the relative economies of the various groups of offices, a series of studies within studies must be carried out upon many other important elements of the problem.

The first of these is the switchboard study. Before the switchboard study can be made, general methods of operating must be agreed upon: such as the method of handling toll business, whether it shall be done wholly upon a toll board or partly upon a toll board and partly direct from "A" positions; whether it shall be done wholly upon a "two-number" basis or substantially upon a "particular party" basis. The best method of handling local business must be determined. It must be decided whether the business shall be upon call wires, or otherwise; what shall be the capacity of the call wire; what shall be the load which will be assigned to the various operators in the system, this in turn being dependent, among other things, upon the character of the service which it is necessary to render.

Having agreed upon these and other fundamental data, the question of the best type of switchboard, whether it shall be full multiple or partial multiple, whether it shall be of the transfer type or otherwise, must be settled. The limit, so far as size is concerned, of the multiple board, or any other type which may be considered, must be determined. Also there must be settled a very large number of questions, cropping out at every turn, involving maintenance and operating expenses and methods. All of these factors having been duly weighed, the maximum size and type of switchboard is found.

The switchboard determinations having been made, the type of cable to be employed must be settled upon. Here again a series of studies is necessary. Of first importance in the cable study is the determination of the standard of transmission which is to be employed, not only for talk between offices within a zone such as Manhattan Island, but also the standard of transmission which it is necessary to maintain between Manhattan Island and the suburbs and between various points in the suburbs passing through Manhattan, and to long-distance points. The importance of this determination will appear when we consider the standard already adopted as the Manhattan standard, which is, assuming the use of the present common-battery apparatus, that the cable employed in Manhattan shall at all times be such that it will give in the worst case a talk as good as could be obtained between two central offices joined by a trunk cable of 10 miles of the standard type having the No. 19 gauge conductors, with a mutual capacity of 0.07. If this standard were lowered so as to employ the use of No. 22 gauge cable instead of No. 19, it would permit the use of a trunk cable costing half as much as that required by the present standard, thus reducing the number of ducts required and in that way substantially affecting the results of the study.

In considering the type of cable to be employed, not only must the standard of transmission be borne in mind, but in determining upon the specifications for the various types of cable needed a long series of special studies is required. These are conducted with a view of ascertaining that form of construction which in each case will give the highest standard of transmission and at the same time preserve the best mechanical conditions needed for hauling the cable in and out of the duct, and also be so constructed electrically and mechanically as to require a minimum of attention from the maintenance point of view. Not only must the various types of cable be carefully fixed upon when considered strictly from the cable point of view, but where suburban and long-distance circuits are to be considered the problem of loading cables presents itself. This involves so much work and study that to give even a brief outline of what it involves would require a paper which itself would extend far beyond the limits of the time allotted for this very general statement of the case.

The general features of the study having been determined upon, and the time having arrived to erect a given central office at a centre previously located, the question of obtaining the necessary real estate and erecting the central office building presents itself. In such cases it is usually impossible to obtain the desired property exactly at the ideal centre. Practical real estate conditions must be met and, of the various parcels of property offered, that is chosen which, taking into account all of the circumstances of the case, results in the lowest annual charges. The distance of a given site from the main subways, the character of the neighboring buildings, the price at which the property can be obtained, the possibility of reconstructing the existing building which may be upon the property, or the necessity of removing it and erecting a new one, and other similar points—all these have to be carefully worked out before a report can be made to the management setting forth the most economical land to purchase.

In other words, before even the land is bought a study must be made of a telephone building which might be erected upon it. Inasmuch as in nearly every case many different properties must be considered, studies for several different buildings must be carried out before the best combination can be determined. After these matters have been decided upon, the details of construction of the building must be further studied. This, as can readily be understood, naturally involves a large amount of engineering work.

Thus far I have hastily sketched the outlines of a telephone development study as it is more particularly concerned with the local plant; but as the local plant must be, as time goes on, more and more intimately connected with neighboring plants in the suburbs, and with more distant plants reached by long-distance wires, most careful study must be given to the best methods of establishing proper relations with those plants.

Without attempting to outline in any detail the nature and extent of the work involved in the methods employed in making a suburban toll-line study, and without going at all into the question of methods of establishing the service to long-distance points, I will say that, considering the broad features of these various classes of conditions, it has been found best, in the particular case which I have taken for my example, to divide the telephone business into three classes; local, suburban, and long distance.

In determining what shall constitute the local class the engineer finds himself engaged in a problem of great magnitude which primarily concerns the business management and which is affected by important public and economic considerations as well as by engineering factors and methods. If the local zone is made too extensive it greatly increases the magnitude of the trunk-line plant from which no toll revenue can be derived. This fact reacts upon the rates in such a manner as to make it impossible to give as low a station rate as might otherwise be the case. This tends to restrict the growth of stations and hence will act as a check upon the growth of the business at large.

The local zones having been established, it must next be decided what shall be the limits of the zones of suburban business, and what shall be classed as long-distance business. Without attempting to explain the various points necessary to be taken into account in determining these questions, I will say that they involve not only those physical factors ordinarily considered to constitute engineering, but also the methods of calling which may be permissible on the part of the subscriber; the entire system of toll rates which should be adopted by the telephone company; the question of what subscribers' names and numbers should be listed in the telephone directory, and how they should be listed; and other questions of a similar nature.

When I review the outline of the methods and magnitude of a telephone development study, which I have here briefly sketched, I am not surprised that some who have only superficially considered the subject are inclined to doubt the value of results obtained in this way. This feeling is strengthened when they consider the nature of some of the fundamental data upon which all of the work rests. For instance, unless there is made a fairly correct forecast of the probable growth of subscribers' lines for a period of 15 or 20 years in advance, it is clear that substantial errors will be made; but more than this, it is necessary not only to forecast the total number of lines expected, but their location must be determined within limits. But this is by no means all. Not only must the location of the lines be decided upon, but the number of calls per day which may be expected over each line must be estimated not only must the number of calls which are expected be determined, but the time of the day during which these calls may be expected must be arrived at in some manner. Even more than this must be done, because it is necessary not only to know all of these facts, but also it must be known where the calls are to go; we must also know what proportion of these are likely to be toll calls, what proportion long-distance calls. Various other factors of like nature must be determined.

There can be no doubt that telephone development as thus viewed, and as correctly viewed, presents abundant opportunities for errors, and that such errors must lead to expenditures of large sums of money, which, if infallible data were obtained, would not be required.

But conceding all this, what is the alternative method which can be followed? If we are to abandon the method of study herein described, what shall be substituted for it? By what plan shall we proceed which will enable us to arrive at a more economically constructed system? What method shall we adopt which will enable us to proceed without answering such questions as those which the present method of study undertakes to answer? It is obvious that what are erroneously called " common-sense " methods might be employed. Buildings might be erected in various locations in a city, chosen after an inspection of the region; they might be substantially constructed and provided with switchboards. These buildings might be joined together by subways, and in the subways cables could be located. Suburban and long-distance trunk-line subways might also be constructed, and there is no doubt that according to such a plan telephone business could be carried on. But have we, after all, in following this method, avoided answering any or all of the questions with which the study undertakes to deal? Most certainly we have not, and while it might not be appreciated, every step taken in this so-called common-sense method really makes a direct, though unconscious and unintelligent, answer to all of the questions propounded and dealt with in the formal study.

If, following this common-sense method, it is decided to erect at a given location a central-office building with a switchboard of a given size, this office must be intended to serve a district of some definite size. If, as would of course be the case, other central-office buildings are erected at other locations, they too must be constructed with reference to fixed districts, and their number must be determined with reference to the expected growth in subscribers; so that, after all, the magnitude of the expected growth is a factor which is unconsciously dealt with. But in determining upon the size of the switchboard and its construction, whether we realize it or not, a definite, though unwitting, answer is made to the questions of what shall be the rate of calling, what shall be the destination of the calls, what shall be their character, and at what time they shall occur. The switchboard and building must be planned for some set of conditions which can be established only by data of this character. Merely ignoring these questions and erecting the switchboard and arranging central offices without making a study does not avoid answering the questions, for by the construction carried out a direct and unequivocal answer to all of these questions is made, yet without giving consideration to any of them or even recognizing their existence.

So it is with subway construction. It is easy enough, after central offices have been located, to plan for a subway joining those offices, but somebody must answer the question as to how many ducts shall be provided in this subway. This can be done by the method outlined in describing the study, or it can be determined at the time by somebody who is opening the streets. It may be done, on the one hand, by engineers after careful study with all of the facts before them, and after having analyzed the statistics of the past and having exhausted all possible methods of throwing light upon the subject; or it may be done by the man in the street with a pickax. Those who would follow the pickax method would not avoid questions which the engineer has recognized and has undertaken to answer. They would, by the number of ducts they would put down and by the character and magnitude of the other construction, give their answer to all of these questions without having considered any of them. As to which of these two methods shall be followed, each telephone company must decide.

Thus far in my outline of that part of the telephone engineer's duties which pertain to development studies, I have dealt more particularly with the physical features of the work. Ordinarily, engineering has to do principally with physical factors, but telephone engineering has not only to deal with physical factors of the utmost complexity, but it has also to deal with commercial questions which, of themselves, would seem to be only remotely connected with the work of the telephone engineer, yet which really vitally affect it. Telephone engineering presents more factors of this nature than, I think, are to be found in many other branches. Take the case of a civil engineer who has before him the problem of constructing a masonry dam. This presents an instance involving solely physical factors. The stability of the dam or its capabilities of impounding the necessary amount of water are in no way affected by any action which the board of directors of the water works company may take with reference to its dealings with their customers.

It is not so with telephone engineering for, as I will presently show, a telephone toll line and switchboard system might be designed in accordance with the highest state of the art and constructed so as to give the best efficiency and yet by the action of the business management, causing the adoption of what might seem to be a reasonable commercial practice, the operativeness of the switchboard system might be totally destroyed. This idea will be readily comprehended when we consider what would happen to the present toll board at Cortlandt Street, operating on the recording basis, using the two-number method of calling, if, by some change in business plans, the particular-party method in use extensively in many other localities were adopted. Only a brief consideration of this case is required to show that, in addition to the present recording operator, a second set of operators would have to be employed, who would be required to call up the subscriber desiring the toll connection and obtain from him the details of his call. The adoption of such a method, while in itself a wasteful and inefficient one, would, in the case I have chosen, require the radical reconstruction of the entire toll-board plant. More than this, the adoption of such a method would render it impracticable to follow the direct-line trunking method which is now possible by the use of the two-number plan of calling. The abandonment of this method would require that such toll lines be handled from toll boards. The magnitude of the revolution which this would make in the engineer's plans will be seen when I say that whereas, by the two-number method, one toll board occupying one floor of the Cortlandt Street exchange is sufficient, there would be required, if the particular-party method were employed exclusively, as many as five or six toll boards occupying five or six floors in the Cortlandt Street building, and requiring five or six times as many operators for their working. This is one of the best examples which could be given as showing the peculiar relation which obtains between telephone engineering and the business management of telephone companies.

Another example, perhaps even more far-reaching in its effect upon the work of the engineer, is the question of whether the telephone company shall charge for its service on the flat-rate plan, or by messages as is now generally the case in this neighborhood.

Under the flat-rate method of charging, in large cities, the more times the customer uses his telephone during the day the greater is the expense to the telephone company. This is due not only to the increased number of operators required, but also to the increased switchboard sections needed for them, and to the increased trunk-line plant. By the method of flat-rate charging there is no motive for the telephone company to encourage an increase in the number of calls. For this reason a flat-rate plan would have to be so engineered, and the rates would have to be so established, that extension stations, desk stands, and other auxiliaries tending to make the use of the telephone easy and therefore more frequent, must be discouraged.

The existence of the flat-rate in such cases would not only be attended by all of these consequences, but many others, one of which in particular is of great importance. I refer to the excessive use of the subscribers' line which such a rate engenders. The consequence of this excessive use is that the busy calls attain such serious proportions that it is difficult, if not absolutely impossible, to give satisfactory service. This trouble from busy calls has at times attained such serious proportions that engineers in various places have exerted extraordinary efforts to mitigate the evil, but without success. This difficulty having been caused by commercial methods could not be overcome by the engineer employing physical methods. The solution of this difficulty lay with the business management, and consisted in the adoption of a proper system of message rates. Once such a method was put into force all of these difficulties which I have enumerated, as pertaining to the flat-rate, and many others which I have not taken the time to explain, disappeared.

While engineers were endeavoring to plan systems in accordance with the flat-rate method, certain difficulties were encountered at every hand. As soon as the message-rate system was adopted all of these difficulties disappeared, and many positive advantages not even suspected as residing in the message-rate plan developed. Under the flat-rate system there was every temptation for the subscriber to send as many calls as possible over one line. This, as I have already stated, resulted in overcrowding the line and was attended by bad reactions of every kind. Those having but small use for a telephone could not afford to pay the high flat-rate which that method of working made it necessary for the telephone company to charge. The consequence of this was that only those having a large number of calls installed a telephone, and those having small use of the telephone made it a practice to use the telephones of their neighbors or did not employ the telephone at all. This practice on the part of the small user was a natural one in view of the fact that under the flat rate the telephone subscriber considered that it cost him nothing to allow his neighbor to use his telephone. All of this resulted in a system largely composed of overloaded lines. Under the conditions obtaining in our large cities, the relief of an overloaded line can be obtained only at the expense of a second line, which in most cases meant doubling the cost of the telephone service. For this and many other reasons the desired relief could not be obtained under the flat-rate system.

By introducing into the large cities the message-rate system, and by placing proper limits on the load which should be carried upon one line, and by providing a graduated system whereby additional lines could be obtained on a basis proportionate to the amount of their use, relief from this overloading was afforded. More than this, under the message-rate system it is obviously for the interests of all concerned that the use of the telephone should in every manner be encouraged. For this reason it became feasible and desirable to install as many auxiliary instruments as possible. This was accomplished by providing for those who required two or more lines a switchboard located at the subscribers' premises, this switchboard being so constructed that as many local stations as might be required could be installed at a moderate equipment charge. Each one of these stations is so equipped that it may be connected with a trunk line to the central office or it may be connected to any of the other local stations without communicating with the central office. In this way not only were the conditions at the central office substantially improved, but another important advantage was obtained; talking between local stations at a local or private branch exchange switchboard could be accomplished without any message charge, thus creating an important by-product costing the subscriber practically nothing. This development not only reacted upon the central office engineering and the general engineering of the plant, but also completely changed the state of affairs with reference to speaking-tube telephones, practically limiting the former speaking-tube system to special and peculiar conditions.

Considering these two examples of the method of charging which shall be followed upon toll lines and the method of charging which shall be adopted upon subscribers' lines, it will be seen that they affect, in a most surprising manner, the work of the telephone engineer. So profoundly do such considerations affect the proper engineering of the telephone plant that it must be said that good telephone engineering cannot exist side by side with a bad system of rates or with improper business methods and organizations. Nothing more forcible than these examples needs to be mentioned in order to show the intimate relations between telephone engineering and business management.

From time to time, engineering methods involving new principles are brought forth. These, when found to affect the methods of the business office, should be submitted to the business management with a full and clear statement of their bearing upon the commercial work of the company. On the other hand there are, from time to time, business proposals and commercial methods which are under consideration by the business management of telephone companies and which, apparently, are only remotely or not at all related to engineering. In view of the many unexpected and important reactions which these proposals may have upon the engineering of the telephone plant, it becomes of the first importance that they should be scrutinized carefully from an engineering point of view, unless it is conclusively apparent that they will be without effect upon the engineers' plans.

Many other instances besides those which I have enumerated might be adduced, such as the effect of the three-minute toll period method of charging upon the various features of suburban trunking methods; and the complicated and disastrous reactions produced by the introduction of many of the party-line systems.

Thus far I have dealt with some of the more general methods of telephone engineering, indicating briefly their nature. One of the very important features of telephone engineering consists in the design and construction of the varied machinery constituting the modern telephone central-office apparatus. A brief statement, therefore, indicating the character of the work which devolves upon the telephone engineer in connection with central-office design is pertinent.

During the past ten years, a revolution has taken place in the design and construction of telephone switchboards, the magneto switchboard, so-called, having given way to the common-battery switchboard. This radical change in telephone practice made new demands upon the telephone engineer, for it became necessary for him to introduce into central-office construction certain elements which had theretofore been utilized principally in engineering work involving electric light and power installations.

In the magneto system, signaling from the subscriber's station to the central office was accomplished by means of a small alternating-current generator turned by hand, and the current supply needed in the working of the transmitter was obtained from a few cells of primary battery located at the subscriber's station. By the introduction of the common-battery system all of this was changed: the magneto generator was dispensed with, as was the primary battery, the current supply for operating the transmitter, as well as that required to enable the subscriber to signal, being drawn from a large storage-battery located at the central office.

In the case of a 10 000-line switchboard, the storage-battery must be capable of giving an average discharge of 500 amperes; and to insure proper working conditions, it must be capable of giving a safe discharge as high as 2 000 amperes. For charging such a battery as this suitable machines must be employed, and these must be present in duplicate or triplicate. The standard machine used for charging a battery of this type delivers 1 000 amperes.

The introduction of currents such as these, and the introduction of these machines and of a large number of auxiliary machines generating currents for special purposes, has resulted in the creation of a power plant at each central office, upon which the operation of the telephone switchboard and apparatus is wholly dependent. The introduction of these larger currents has necessitated most careful and refined methods of fusing and protecting the delicate telephone apparatus. These protective methods, while following the general principles of such methods in electric light and power practice, are more refined in their working and call for a hitherto unattained degree of precision in the manufacture of such apparatus.

While the storage-batteries and auxiliary machinery employed in telephone power plants are far from equalling the magnitude of similar apparatus employed in electric light and power stations, nevertheless they have become such a vital element of the successful engineering of a telephone central office, that they require on the part of the telephone engineer a special knowledge of this branch of electrical engineering, which was formerly not requisite. This class of apparatus must also be considered by the telephone engineer in a special manner, for not only must it be properly constructed from the electric light and power point of view, but peculiar conditions must be provided for on account of the association of this apparatus with such a delicate instrument as the telephone.

Where a dynamo is to be constructed to operate incandescent lamps, let us say, certain minute fluctuations in the potential of the machine are permissible. Were such a machine, however, to be used in connection with telephone circuits, these fluctuations in potential would be sufficient to produce such constant humming in the telephone as to render it inoperative. Hence a greater refinement of the construction of these machines in this respect is imperative where they are employed in the telephone power plant.

So it is with the storage-battery. Where a number of telephones are supplied by current from one storage-battery, even almost infinitesimal changes in the voltage of the battery might be propagated to the telephone lines connected therewith and produce disturbances. For this reason, storage-battery practice from the telephone point of view presents problems which are different from those encountered elsewhere.

One of the interesting and important developments in the modern common-battery switchboards is the extensive use which has been made of incandescent lamps in signaling. Hundreds of thousands of these lamps are now used for telephone signaling, and the requirements of the telephone art have called for special refinement in the design and manufacture of these lamps.

While the common-battery switchboards as now used in all of the large central offices represent a revolution in methods as compared with the magneto system, there are certain elements formerly used in the magneto system which have persisted. Among these is the multiple-board principle. This principle, as is well known, consists in extending a number of lines to different points in the switchboard so that it is possible to connect with them at any one of these points. The multiple system is opposed to the transfer system, which is one wherein the lines are not so extended or multipled to different points, but proceed directly to a special location from which trunk lines extend to other parts of the switchboard, so as to provide for making the necessary connections. It is safe to say that during the past 20 years there has been no question of switchboard design that has been the occasion of so much discussion and controversy as that pertaining to the extent to which the multiple principle should be adopted. It is interesting to note therefore that no type of switchboard of any magnitude is now seriously considered which does not in a very substantial manner utilize this multiple principle.

In a self-contained central office, with relatively few trunk lines extending to other offices, it is found most economical to multiple all of the subscribers' lines to each section of switchboard. In very large cities where a number of central offices are required and where the amount of trunking between the different central offices is relatively large, the advantage of multipling all of the subscribers' lines to each section is not so apparent as in the case of the self-contained office, and this fact has led many to the conclusion that for such situations multiple boards are not adapted. But this is going further than the facts warrant, for while it is true that the advantage of multipling the subscribers' lines to all of the sections of the switchboard becomes less and less as the percentage of trunking increases, it is still a fact that the point is never reached where the multiple principle itself should be entirely abandoned.

The truth of this proposition may easily be established by assuming that in a large city all of the calls must be trunked, and that none of them are local to the office in which they originate. In such a case as this it is obvious that nothing could be gained by extending all of the subscribers' lines before each of the operators. On the other hand, it is still essential that the outgoing trunk lines should be extended, or multipled, before all of the subscribers' operators, and all of the subscribers' lines should be multipled before the trunk operators. While the case of an office without any local calls is one which could not occur in practice, there are situations in which the amount of local calls is so small that it will not pay to multiple the subscribers' lines to all of the subscribers' operators. Just when this point is reached is a question to be determined in each case.

Thus far, the instances where it has been found possible to omit this multipling of the subscribers' lines are few, but as time goes on the number of these cases must increase; but at no time, so far as can now be seen, will the point be reached where the multiple principle itself will be abandoned. Even in the automatic switchboards, which constitute one of the most interesting of the recent developments, the multiple principle is found to be essential to the working of all types of automatic boards thus far proposed, wherever the switchboard is of any substantial magnitude.

With reference to this matter of automatic telephone switchboards, I may say that such types of apparatus have during the past few years become a matter of great interest and the subject of much discussion among telephone engineers, and as I have made a number of special investigations into this subject I think it would be of interest if I here briefly state some of the results which I have obtained.

Upon a first view of the case, the idea of using automatic machines and thus doing away with the labor of telephone operators appeals with much force, and the wonderful things which have been accomplished by labor-saving inventions naturally come to mind. Among all of these projects for saving labor by automatic machines none seems more wonderful than the little machine which, when manipulated by the subscriber, will put him into communication with anyone out of thousands or tens of thousands of people scattered over a wide area. But in order that an automatic telephone switchboard should be properly called a labor-saving machine, it must accomplish its work at an expense entailing less annual charges than would be required by the system which it attempts to displace. If it should be found that the annual charges of operating the automatic system were equal to or greater than the annual charges of operating the manual system, then the automatic system would not be a labor-saving one, and, considered from the standpoint of costs, would be a failure. Whatever merit it would have, in that event, must be looked for in some very superior results in the way of service. From these two points of view, I have considered the merits of the various automatic switchboard systems which have thus far been installed.

I find that, taking into account all of the factors involved, and which go to make up the total annual charges which could properly be placed against the automatic switchboard system, on the one hand, and the manual system on the other hand, leaving out of account switchboards suitable for use only in small villages and making comparison up to switchboards of 10 000 lines capacity, that the annual charges upon the automatic system are substantially greater than the annual charges upon a manual system operated on the common-battery multiple plan. From the standpoint of costs, therefore, the automatic system fails when placed in competition with the common-battery multiple-board operated manually.

Having found that the automatic system could not successfully compete with the manual system in point of costs and annual charges, I made a careful investigation to determine whether the automatic system possessed any advantages of working over the manual system which might compensate for the extra annual charges which its use necessitates. For this purpose there were made about 7 500 service tests on manual switchboards and automatic switchboards operating under practical conditions in different parts of the country. The results of these tests showed that the manual system possessed a most substantially greater degree of reliability than the automatic system. The difference in speed of connection between the two systems was so small as not to constitute a practical factor, the time elapsing between the start of the call and the answer of the called subscriber being in the case of the automatic system 19.9 seconds and in the case of the manual system 21.7 seconds. These figures include the time taken by the subscriber to answer, and even this small difference of time was found to be due to the fact that the subscribers whose lines were tested answered somewhat quicker in the automatic system than in the manual system. It will be seen, therefore, from these tests that the automatic system possesses no practical service advantages over the manual system and that it contains no elements sufficient to warrant any part of the extra cost which its use involves. A full consideration of the details of the comparison of these types of switchboards would lead me far beyond the limits assigned to this paper and would only result in showing that the alleged advantage of doing away with the operators at the central office imaginary and not real.

All of the foregoing relates to switchboard systems smaller than 10 000 lines, no automatic switchboard of larger size having been installed.

In order to determine whether for systems larger than 10 000 lines the automatic principle might be applicable, I made a study, assuming a system of 100 000 lines to be equipped with automatic switchboards, and compared this with a similar system equipped with common-battery multiple switchboards operated on the manual basis. Here again the comparison is in favor of the manual board, both in point of annual charges and in respect to the service.

In applying the automatic switchboard to this 100 000-line study, it was necessary to leave out of consideration a very large class of difficulties which crop out at every turn when the attempt is made to apply the automatic principle to the complex conditions which obtain in and around all large cities. Inasmuch, however, as the study showed that the automatic system is inferior to the manual system for a 100 000-line plant, it became unnecessary to take into account the large number of adverse factors which must be charged against the automatic plan of working. So important are these factors that it is safe to say that even if the annual charges on the automatic system were substantially less than those on the manual system, they would constitute such a serious objection to the automatic system as to bar its use.

Throughout these investigations the importance of retaining at the central office operators to receive and attend to the subscribers' calls has been emphasized in so many important and unexpected ways that I have no hesitation in saying that no plan thus far employed, which requires that the subscriber should operate a machine and send his call automatically to the central office, can successfully compete with the plan which requires that the subscriber should remove the telephone from the hook and send the call orally to an operator at the central office.

Closely associated and interwoven with the design and construction involved in telephone engineering is the matter of the materials to be used. To the proper choice of material as well as to their proper arrangement in the plant, the telephone engineer must devote serious and constant attention. All materials which are permitted to form a part of the telephone plant must be carefully studied by the telephone engineer so as to obtain out of all those possible to use those which offer the best combination of first cost, durability, low annual charges, and high efficiency.

Considering the almost innumerable varieties of materials used, all of which must be covered by standard specifications, the work of this branch of telephone engineering, taken by itself, would require so much time to describe that I will not attempt to enter into it in any detail, except to say that it constitutes one of the important duties of the telephone engineer.

Intimately connected with this matter of the choice of material and making the specifications therefor is the complementary function of accepting or rejecting that which is offered. The drawing up of the specifications must be attended to with care so that they may be placed in the hands of the purchasing agent, and be sufficiently intelligible so that any manufacturer or person skilled in the art can understand their purport, and supply without further information the articles desired. The drawing of such specifications is of great importance, for not only must the article desired be clearly described, but the language used must be such that no material other than that desired can be furnished under this specification. At the same time, while every precaution must be adopted in the specification to exclude undesirable material, care must be exercised that undue and excessive requirements should not be specified. Otherwise the cost of the materials would be unnecessarily increased. Here, as well as at almost every turn in the work of the telephone engineer, there is no safe side. If the specification is made too rigorous, and calls for material of a quality in excess of that which is demanded by the nature of the construction, loss will result. On the other hand, if the specification is drawn loosely or so as to admit inferior material, loss will result owing to defective working of the construction in which such materials would enter.

So far as I have gone, I have described the more typical functions of the telephone engineer. In addition to this, there are constantly arising questions demanding special investigation. The range of these questions is almost unlimited, and their adequate treatment requires most laborious and serious effort on the part of the telephone engineer. While their range is so extended as to touch at some point almost every field of engineering and scientific progress, and while the telephone engineer cannot be expected to be expert in all departments of scientific investigation, he is required to direct such investigations, employing, as his judgment may dictate, experts in various departments to report upon those phases of the work in regard to which they may be best qualified to speak.

Thus far I have discussed the work of the telephone engineer without particularly calling attention to his relations to the telephone organization at large. This relation can best be understood by stating that the telephone engineer in every well-organized telephone company must, in the first place, broadly determine all of the important features of the plant of the company, and he must in detail decide what shall be the nature of the construction and the method of operation of every single item which constitutes the physical property of the telephone company. If, through defective design, a telephone cable is found to be ineffective mechanically or electrically, it may be said in a properly organized telephone company that the fault lies with the telephone engineer. If, through defective design, the telephone switchboard is found to be unsuitable with respect to its maintenance or operation, the fault lies with the telephone engineer. So on through all of a multitude of items which constitute a telephone system. If, in a well organized and well administered telephone company, the plant is not constructed in accordance with the best state of the art, the fault lies with the telephone engineer.

That this must be so will be made clear by describing the method which obtains in well organized telephone companies of getting from the board of directors the necessary appropriations for carrying out all construction and reconstruction work. Under such conditions a development study will have been made and will have been approved by the business management. The traffic department will have, from its careful watching of the extent of the available facilities, given due notice of the time at which additions, changes, or renewals of switchboard facilities may be required, all of which are presumed to have been contemplated in the broad plans already approved by the business management. The construction department will have, from its constant watching of the available cable and line facilities, given due notice of such changes, renewals, and additions as may be required in these parts of the plant to accommodate the growing business and fit in with the approved general plan. In the case of the traffic department, the demands of the service having been thoroughly studied by them and the essential data having been supplied to the engineer, the necessary detail studies, plans, and specifications are prepared by him and an estimate prepared for the work required. A case will be made out setting forth the nature of the work and the necessity therefor, and an estimate showing its cost and a specification describing the work in detail will be submitted to the management, and if in proper form, it will be duly approved. The estimate and specification will then be turned over to the proper department and, depending upon the nature of the construction, the work will be executed by the telephone company itself or by a contractor.

This work must be supervised, as far as may be necessary, by the engineer, and upon its completion he must accept it or reject it. Having accepted it and having made a report to that effect to the business management, the transaction is completed. By this acceptance of the work, the engineer assumes full responsibility for its efficiency.

So it is with the cable plant, except in this instance, as a matter of administrative efficiency, the superintendent of construction may submit detailed plans for the extension to the cable and wire plants, following, however, general lines which have already been standardized by the engineer. These plans and specifications having been accepted by the engineer, and the work having been passed through the regular routine, the ultimate responsibility rests in the engineer's office.

So it is with other features of the work. From beginning to end, the engineer is thus placed in a position to exercise a veto power upon any adverse methods which might otherwise be allowed to creep in.

The carrying out of this estimate system in this way places final responsibility upon the engineer and recognizes in the most practical manner one of his most important functions, which is to coördinate the various elements which must be put together in such a manner as to avoid conflict and produce a consistent symmetrical organism, each part of which will be designed and constructed with due reference to the functions which it must perform and also with due regard to the functions and importance of all other elements in the system.

The importance of this coördinating function cannot be overestimated and it is only at some central point that such function can be exercised. Being judged from the maintenance point of view, a piece of apparatus might have qualities of a high order; but when considered with reference to its effect upon the traffic, difficulties might be discovered which would entirely overweigh the maintenance advantages. In such a case the conflicting claims with respect to the apparatus must be judiciously considered by the engineer, and his decision must be rendered with a view to producing the best net result.

Again, systems might be proposed which, considered solely from the maintenance, construction, and traffic points of view, might seem to possess all of the advantages of an ideal arrangement; but when considered from the standpoint of the efficiency of transmission might be found to involve an impairment of transmission on one hand or such increase in cable and line costs on the other hand as to render its use out of the question.

In order to exercise proper coördinating functions, it is essential that the engineer should be placed and should maintain himself in such relations with all of the departments of the telephone organization that he may get from them and fairly consider all of the projects and ideas pertaining to the design, operation, construction, and maintenance of the plant which naturally originate in such departments when they are conducted with proper efficiency.

Viewed from this standpoint, it will be seen that while the function of the engineer with relation to the plant is of the utmost importance, nevertheless the work of the traffic, maintenance, construction, and other departments has such an important bearing upon the whole question, that the successful engineering of a telephone system must be regarded not only as the work of the engineer himself but as the work of all of the other departments concerned. Not only this, but what is still more important, the successful engineering of a telephone plant depends upon proper business management, as I have indicated by several striking examples. Without an intelligent, progressive, and broad-gauged business management, there cannot be good telephone engineering.

DISCUSSION ON "TELEPHONE ENGINEERING," AT NEW YORK, FEBRUARY 23, 1906.

Thomas D. Lockwood: In the early years of the telephone exchange, when the telephone engineers of the present time—yes, and the telephone business managers of the present time—were learning their business by hard knocks, we all thought, having no idea of course of what the telephone exchange would grow to, that the greatest and most wonderful feature of telephony was the invention of the telephone itself; and of course in a sense that was so and is so. But when all is said and done, and we have given to the telephone and its inventor all of the credit, honor, and glory to which it and he are unquestionably entitled, I think we should still have enough to spare for the men who have built and perfected the telephone business, who have constructed and perfected the telephone exchange, and who have designed and organized the art of telephone engineering, as expounded in the paper we have just heard.

In the first five years of telephone exchange history, one of its most noticeable features was that each individual exchange throughout the country had its own peculiar system, its own switchboard, and its own method of operation. Each exchange manager thought his own system was the best, and that there was no other worth looking at. This stage may be called the chaotic stage of telephone engineering.

Then came a time when some began, blindly perhaps, to see that this way was scarcely adapted for a permanent business; and that of three or four hundred different systems, it was not possible that each and all could be the best or the worst; and it dimly appeared to some that a uniform system of engineering was desirable, and that standardization was necessary; and work along these lines was done, albeit still indefinitely. We may regard this period as the tentative stage of telephone engineering.

Then at last comes the era of real telephone engineering, and in this the author of the paper of this evening was one of the pioneers. I could speak of his early career, but time will scarcely permit. Some of us, however, can readily recall a paper prepared by him for this INSTITUTE as long ago as March 17, 1891, entitled "Inductive Disturbances in Telephone Circuits;" and we remember with satisfaction its philosophic considerations and conclusions.

I did not obtain a copy of Mr. Carty's paper until this morning just before starting for New York, but I have read it over once or twice already with both pleasure and profit, and expect to read it again; and to keep it by me, as one does a volume of Shakespeare, for constant and frequent reference.

The first point to attract my attention was the author's comment that " not so many years ago " the relation of a telephone building to the " existing and probably *future* subscribers " received but scant consideration. Yet this outlook into the future, and the possibilities and probabilities of growth is now—and justly so—regarded as one of the most important considerations of modern telephone engineering. This word " future " therefore brings out the responsible character of the work of the telephone engineer most sharply. I do not suppose that in any other branch of engineering is it so necessary to " take thought of the morrow."

Mr. Carty mentions that the life of the central-office switchboard may be placed at about 15 years. In this, he is perhaps conservative. Judging from the past, and taking both wear and tear, and obsolescence into consideration, I should almost have been inclined to place the figures even lower. In a paper read at Chicago in 1901, at a convention of Public Accountants, by George Wilkinson, Vice-president of that society, the author mentioned that he had recently had occasion to examine closely into the depreciation of telephone exchange plant, and was inclined to " fix the life of a switchboard at from 12 to 14 years."

It is most interesting and instructive to note that the " standard of transmission " is a pre-requisite to a determination of the type of cable to be employed; and the standard adopted in Manhattan, requires the use of such a cable as will in the worst case permit as good telephonic transmission as could be obtained between two central offices joined by a trunk cable of 10 miles of the standard type having No. 19-gauge conductors, with a mutual capacity of 0.07. The good quality of telephone talk in New York is thus accounted for.

Mr. Carty points out, that while the development of telephone engineering on the correct lines of studying the needs and the quality of work required for a period of years to come is not unlikely to be more or less productive of costly errors, there is really no other way; and that any other way adopted would inevitably keep in mind, albeit unconsciously, the necessities of the case; and would by its operations tacitly, though blindly, acknowledge and endeavor to meet them. The paper is most convincing on this point, and it is reasonable and rational to believe that any such blind procedure as might thus alternatively be adopted, would be productive of far more errors and far greater expense, than can possibly be the outcome of the methods of careful and systematic study.

Referring to the operation on the recording basis of the present toll-board at the Cortlandt St. central station, certain expressions are employed, which may not be entirely clear to every one, and which, for the benefit of the many who are going to read the paper, I hope Mr. Carty in his concluding remarks will explain a little more fully. These are the "two number method of calling" and the "particular party method." I am not quite sure that I myself understand the exact significance of these expressions, and perhaps others also would like to be informed.

The discussion by the paper of flat and message rates is of vital interest; and the advantages generally of the message-rate plan seem so plain in the majority of cases, that we are inclined to wonder that they were not recognized earlier. But it is to be kept in mind that telephone men themselves had to learn their own business little by little; and that after all, though adherence to flat rates so long was doubtless in most cases an error, it was an error which had been persisted in by the hotel business for many years. When I came into the country 39 years ago it was hard to find a " message-rate " hotel, anywhere, even in New York. Now it is becoming difficult to find a " flat-rate " hotel.

It may be, that to some, Mr. Carty's graphic description of the manysidedness and multifariousness of the conditions, essential studies, and exacting requirements of telephone engineering, and of the numerous duties and requisite qualifications of the telephone engineer who is called upon to unite in himself the functions of an engineer, a diplomatist, and an actuary, may seem overdrawn, idealized, and impossible of attainment. This however is not so. Nothing less than the constant practice of just such engineering; nothing less than precisely the work of just such a telephone engineer, could have made the telephone system of New York what it is to-day.

The paper commands my heartiest admiration. Its propositions must meet the heartiest assent of every modern telephone engineer. It is replete with graphically stated facts, and I am glad to know that it will be a part of the annals of this INSTITUTE.

President Wheeler: I know of an incident that is worth mentioning, as I think it serves to show the great growth of electrical work of all kinds. In my early experience I was employed by a man who had the rights for the telephone system in New York City, and he felt rather pleased because he had just succeeded in inducing some one to buy these rights from him for $10 000.

Bancroft Gherardi: There is one phase of telephone engineering which Mr. Carty has necessarily only touched upon briefly. That is the engineering which, as a matter of administrative efficiency, should be done in the various executive departments of the organization. The most conspicuous examples of these are the engineering which must be done in the department under the control of the superintendent of traffic, and in the department under the control of the superintendent of construction. The engineering done in the traffic department is in charge of an engineer usually designated as the traffic engineer, who has reporting to him a sufficient number of assistants to do the required work. This engineer is charged with responsibility for a large amount of work, which, while essentially engineering in its character, is nevertheless so closely related to the detail methods of operation in use in the traffic department, and the detail administration of that department, that to have it done in the office of the chief engineer of the company would require that the chief engineer should keep complete records in all detail of matters going on in the traffic department, and be familiar to the last detail with a vast number of administrative questions concerning that department.

One of the functions of the traffic engineer is to watch carefully the growth of the business with reference to the requirements for additional equipment of all kinds for switchboards, and at a proper length of time in advance to make a report stating that additional equipment is required, and recommending the extent of such equipment.

To give an idea of the complexity of this function alone, I might say that the following are some of the details which the traffic engineer has to watch in connection with each large switchboard in the system:

1. The number of subscribers' lines available in the multiple.
2. The number of switchboard positions available for subscribers' operators.
3. The number of switchboard positions available for trunk operators of various classes.
4. The number of incoming trunk cords available for incoming trunk lines of various classes.
5. The number of call-wire circuits available for calling circuits.
6. The arrangement of answering jacks so that it may be possible to give all operators at the switchboard proper loads.
7. In addition to these items in the switchboard itself there are all of the various items concerning the information desk, the assistant manager's desk, and the manager's desk—all elements of the plant which are of the utmost importance in connection with an efficient operation of the system as a whole.

The report recommending additional switchboard equipment is made to the superintendent of traffic, and if approved by him, is transmitted to the chief engineer. The report if in proper form gives the essential facts upon which the recommendation is based, and enables the chief engineer to pass promptly on the matter. As will be seen by this routine, the chief engineer does not necessarily have to concern himself with the detail affairs of the traffic department, while at the same time he is not relieved of the responsibility in regard to the amount and character of plant provided.

Another very important function of the traffic engineer is to watch the constant growth of the business trunked between various offices and handled over toll lines between various sections of the territory. It is his duty to originate recommendations for additional trunk circuits that may be required to take care of this business. These recommendations when requiring additional plant are in due course transmitted to the chief engineer, with a request that a formal estimate be prepared and an appropriation asked for. Thus the matter comes before the chief engineer, and again, as in the case of the switchboard equipment, the final responsibility is with him.

Numerous cases arise in which it is necessary that detail studies should be made of various operating methods. These studies can best be made by some one forming part of the traffic department, and it is in general the traffic engineer's duty to do such work. The results of these studies, when they indicate any important change in the operating methods of the company, are submitted to the chief engineer with the facts in the case, and he in this way passes upon the matter.

In the construction department there is necessity for a construction engineer, who performs with reference to that department functions similar in their general nature to those performed by the traffic engineer in the traffic department. One of the very important functions of this construction engineer is to keep constant watch of the cable situation, and to recommend at a sufficient length of time in advance additional cables or extensions of cables to take care of the business. These recommendations are made by him to the superintendent of construction, and by him transmitted to the chief engineer with a request for estimate. Upon being received by the chief engineer they are checked up, and thus again the responsibility is finally with him.

In cases such as this, where the administration of the construction department and its engineering work are efficient, the principal work of the chief engineer in connection with such cases is to see that the plans proposed fit in with the general studies and general scheme of development. He also sees that the plans provide for the use of standard materials or materials appropriate to the particular situation in question.

An important function of the construction engineer is with reference to the rights of way necessary to carry out contemplated pole-line construction. Such rights of way are so intimately associated with the final planning of the construction, that they must be obtained prior to the preparing of actual plans for the work. At the same time the rights cannot be obtained without careful engineering consideration as to what such plans should be. Hence it has been found that in a large company the rights of way had best be handled by the construction engineer, and the right-of-way work is a very important part of his duties.

From an engineering standpoint I think it is safe to characterize the development of an organization having engineers in the construction and the traffic departments as one of the important steps which lead to efficiency of the operating organization as a whole.

C. P. Steinmetz: Telephony has always been very fascinating to me, when considering it as a transmission of sound over great distances, and by currents so minute that only recently, and by the most sensitive oscillographs, has their record been reproduced on the photographic film.

To the electrical engineer, even if he is not directly interested in the industrial application of the telephone, telephony is of great interest and highly instructive as a form of transmission of electric power, entirely different in its purpose from the high-potential transmission of larger powers, and different therefore in its methods and in the problems involved in its successful accomplishments.

In electric power transmission, as usually considered, the problem is to deliver at the end of the transmission line as high a percentage as possible of the power sent into the line. That is, the efficiency of transmission is the principle consideration.

Not so in telephony. Here the problem is to deliver at the end of the line the electric power in the form of an alternating current of the same very complex wave-shape as the current sent into the line; that is, with the same relative intensity of all the harmonics of the complex wave representing the sound.

If it were a question of delivering sufficient electric energy to operate the telephone, the problem would be very easy; the telephone is so sensitive an apparatus, that enough energy could be transmitted from San Francisco to New York, and even farther still—over a trans-atlantic cable to London—to operate the telephone with an almost insignificant expenditure of energy at the sending end. But with such a long distance, while the sound could be heard, the articulation would be lost; only the fundamental wave would arrive, the higher harmonics being almost entirely suppressed. But in speech the higher harmonics are of main importance, and not the fundamental wave. It is the higher harmonics which differentiate sounds, and so constitute articulate speech; let them be blurred and the result is a noise rising and falling in pitch, but no articulate speech.

In telephony the problem therefore is to transmit electric energy, practically regardless of efficiency, with as little destruction or deterioration of the very complex wave-shape as possible, while in high-potential power transmission the desire is to have only a fundamental sine wave and none of the higher harmonics. The transmission of the higher harmonics is what constitutes the problem of telephony.

J. J. Carty: Mr. Lockwood has asked me to explain what is meant by the expression " two-number business." This is a method of designating certain toll calls wherein the subscriber, in giving the call, employs the number rather than the name of the party wanted. Business handled in this way can be conducted more expeditiously than when the subscriber calls by name, as is the case with certain classes of business.

The name " two-number business " probably arises from the fact that the recording operator writes upon the ticket two numbers, one of them being the number of the party called for and the other the number of the party calling.

A paper presented at the 205th Meeting of the American Institute of Electrical Engineers, New York, March 23, 1906.

SOME FEATURES AFFECTING THE PARALLEL OPERATION OF SYNCHRONOUS MOTOR-GENERATOR SETS.

BY J. B. TAYLOR.

In this paper the phrase "synchronous motor-generator" means an alternating-current synchronous motor directly connected to an alternating-current generator. The author's intention is to point out some of the details of construction, connections, and method of operation that need to be considered in order that a desired division of load will result when such units are operated in parallel.

USES OF SYNCHRONOUS MOTOR-GENERATOR SETS.

1. The most common use of motor-generator sets is to effect a change in frequency, so that standard lighting apparatus, alternating-current arc lamps, etc., may be operated from a system of lower frequency designed primarily for railway or power purposes. For example, a railway system distributing high-tension current at 25 cycles to a number of sub-stations may desire to take over, or develop, a lighting load; a motor-generator set, consisting of a 25-cycle synchronous motor and 60-cycle generator, can be employed for this purpose. Such a set, in addition to giving the desired change in frequency, has several incidental advantages for lighting purposes; for by means of an automatic regulator on the generator, constant voltage may be maintained on the lamp circuits independent, within limits, of fluctuations of speed and voltage on the 25-cycle system.

2. Such sets are also used as a means of interchanging power

between systems already established and operating at different frequencies.

3. The operation of the single-phase railway motor calls, in some cases, for a motor-generator set with inverted frequencies; that is, a 60-cycle synchronous motor in connection with a 25-cycle generator. With such a combination there may be obtained an energy transfer from a three-phase system to a single-phase system without unbalancing the three-phase system.

A load with low power-factor on the 25-cycle end of such a set will have no more effect on the regulation of the system which supplies the motor than a load of the same number of kilowatts at unity power-factor.

DIFFICULTIES EXPERIENCED WITH EARLY INSTALLATIONS.

Considerable difficulty was experienced with some of the first of these sets; for instance, a set on being started and connected in parallel with others already carrying a load would, on some occasions, refuse to take any of the load and at other times it would take a great deal more than its proper share of the load. These troubles were due, mainly, to lack of consideration of the possible combinations of phase relations of any given set depending on connections and load. It is also evident that suitable switching devices and method of procedure for a 10-pole—24-pole combination, operating between 25 and 60-cycle systems, will not be suitable for a 4-pole—10-pole combination operating between 25-cycle and 62.5-cycle systems. As a result of these early troubles, a number of station operators retain the impression that unless certain special combinations of field excitation are used at the instant of parallelling, the proper division of load will not result; and that once being connected in parallel, further changes in field excitation will have no effect.

ANGULAR LAG AND PHASE DISPLACEMENT.

In order to understand the operation of a synchronous motor, it is necessary to have some definite reference point. This reference point must rotate in synchronism with the electromotive force of the system connected to the terminals of the synchronous motor, and must also maintain the same phase relation to the electromotive-force wave. In Fig. 1, let A represent the reference point rotating about the point O, and let $N\ S$, etc., represent the four revolving poles of a synchronous motor. Since the reference point A and the poles

$N S$, etc., rotate at the same speed, and since only the relative positions need be considered, the diagram at rest can be examined with the same result as if the diagram rotated at synchronous speed with the observer stationed at the point A. If Fig. 1 represents the relative positions of reference point and field for the condition of no load on the motor, it is apparent that with a load the relative positions will be as represented in Fig. 2, in which case the rotating field will lag behind the no-load position by an angle $A\ O\ N$, the number of degrees in this angle being dependent on the load, the number of poles, the field excitation, and on the magnetic and electrical design of the machine. If this motor be coupled to a generator having twice the number of poles, as indicated by $n\ s$, etc., it is apparent that the lag-angle $A\ O\ N$ will cause the generator electromotive force to lag a corresponding number of electrical degrees, which will be twice as many as the number of electrical degrees displacement on the motor; for example, with a 4-pole motor and 8-pole generator and angle $A\ O\ N$ 10 degrees (mechanical), there would be a corresponding electrical displacement of 20 degrees for the motor and 40 degrees for the generator.

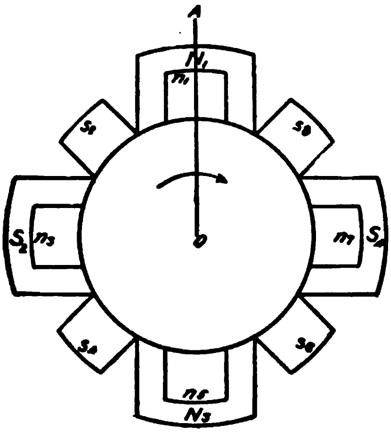


Fig. 1
4-Pole Synchronous Motor.
8-Pole Generator
No Load

In addition to the phase displacement of the generator electromotive force due to the angular lag of the motor, there is a further displacement between the electromotive force of generator of set under load and set under no load, due to the phase difference between the generator induced electromotive force and the generator terminal electromotive force; the amount of this displacement depending on the amount and power-factor of the load, and also on the design of the generator. Fig. 3 is a vector diagram showing the electromotive force of the bus-bars (or machine running under load), current, inductive drop, and resistance drop in generator, and induced electromotive force. In this diagram the power-factor of the load on generators is assumed at 100%.

Fig. 4 is a similar vector diagram, with a power-factor 70%.

These two actions taken together give a phase displacement between the generator terminal electromotive force under load and under no load as indicated in Fig. 5; angle α being due to synchronous-motor lag, angle β to generator reactance; the angle θ is the sum of these two.

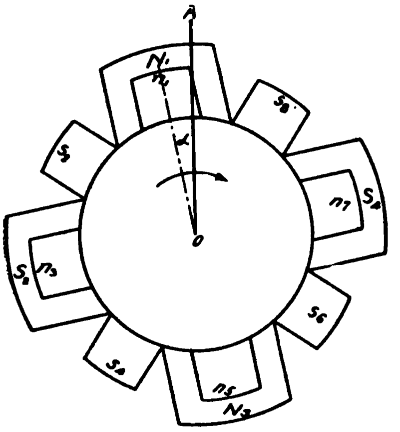


Fig. 2
4 Pole Synchronous Motor
8 Pole Generator
AON = Lag Angle due to Load
Direction of Rotation shown by Arrow

REQUIREMENTS FOR EQUAL (OR PROPORTIONAL) DIVISION OF LOAD.

Two sets of identical construction, connected in parallel on both motor and generator ends, will each take the same amount of load, provided field excitations are equal. If either set has a motor or a generator designed for closer regulation than the corresponding machine of the other set, the set having the closer regulating machines will take more than its share of the load.

Referring to Fig. 5: for a given load the angle *θ* will be smaller the closer the machines regulate. The closest regulating set, therefore, will have an electromotive-force wave in advance of the other set, thus taking more load, which tends to increase the angle; while the other set will take less load, which tends to decrease the angle. The machines will, therefore, settle down at that division of load which makes the angle *θ* the same for both. The division of load is stable, as any displacement tending to increase the output from the generator of a set will also tend to reduce the load assumed by the motor; and vice versa.

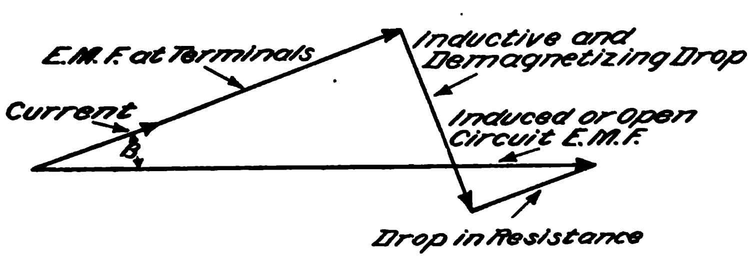


Fig. 3.

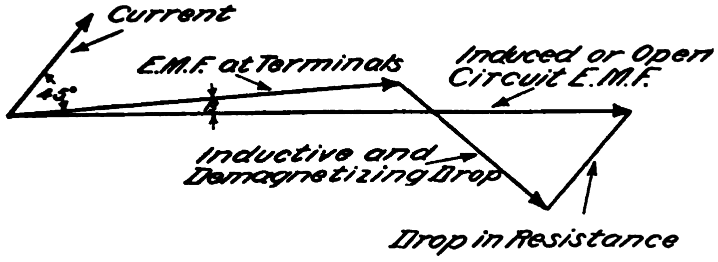
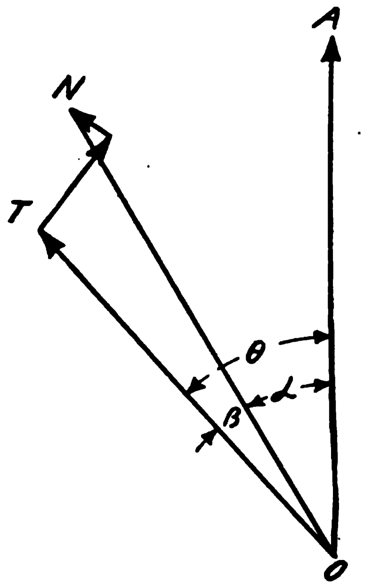


Fig. 4.

In the previous discussion it has been assumed that the mechanical construction of the two sets is identical. Since identical mechanical construction involves perfect alignment when machining the key-ways, milling slots for pole pieces, armature laminations, etc., it is difficult to construct two sets having an initial phase difference of less than two or three degrees; and this difficulty increases with machines of different design and rating constructed at different times. This point is of first importance in machines of this class, as a manufacturing company may any day receive an order for a machine, say, of 1 000-kw. capacity to operate in parallel with machines of 200 or 500-kw. capacity already in service and constructed four or five years ago. If slight differences in machining cause the generator of one set to have an electromotive-force wave in advance of the wave of the other sets, this machine will, at no load on the system, reverse the action of the other sets, causing the generators to act as motors, and the synchronous motors to act as generators.

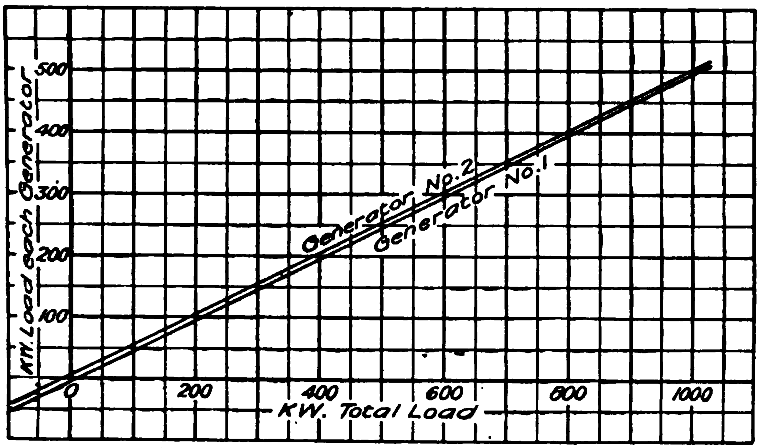


Phase Relations of Generator E.M.F.
OA = E.M.F. on open circuit
ON = E.M.F. induced under load
OT = E.M.F. at terminals under load

Fig. 5.

Fig. 6 shows the interchange of load between two sets constructed at the same time, but differing by approximately four degrees on the generators. These sets are of 500-kw. capacity, and when connected in parallel with no load there is an interchange of 11.6 kw. between the generators. In this particular case no energy will be returned by the synchronous motor of the lagging set, as 11.6 kw. is, obviously, insufficient to supply the losses in 1 000 kw. of apparatus. The set which is four degrees in advance of the other will, when under load, carry approximately 10 kw. more than the other set. The difference in this case being approximately two per cent. of the rating, is of little importance.

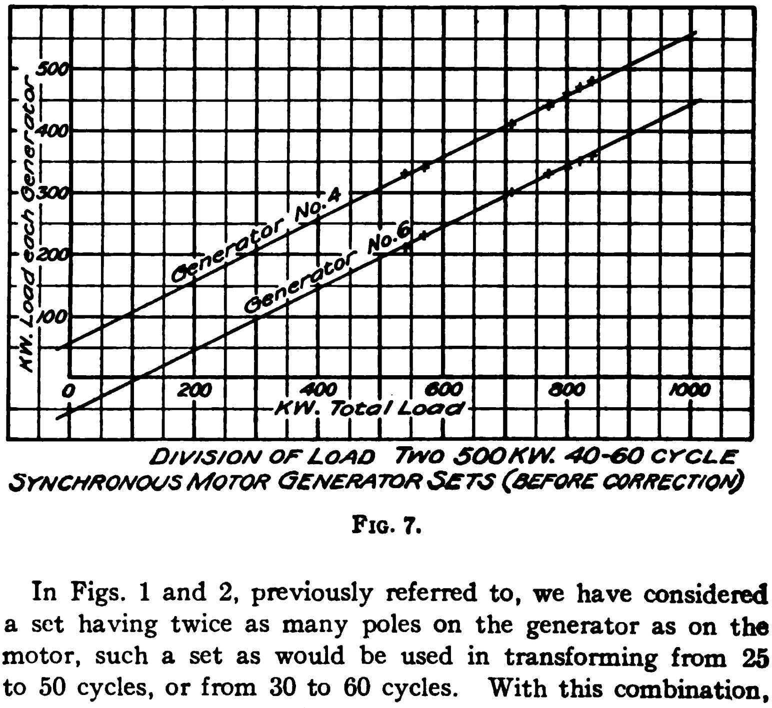
Fig. 7 shows the division of load between two machines having a greater difference in construction. In this case these sets were also rated 500 kw., but one machine took approximately 110 kw. more than the other. This difference, a matter of 20%, was corrected by drawing off one of the revolving fields, and replacing it with a new key so as to give an offset of a few hundredths of an inch. Now there is a difference of only 10 kw. in the load taken by the two sets; this is satisfactory, being only 2% on the rating of the machine.



DIVISION OF LOAD TWO 500 KW. 25-60 CYCLE SYNCHRONOUS MOTOR GENERATOR SETS

FIG. 6.

Division of load among seven machines in the same station operating in parallel is shown in Fig. 8. These machines are shown in Fig. 9. Three of these machines are of 250-kw. capacity, three of 500-kw. capacity, and the other of 1 000-kw. capacity. It will be seen that the division of load is very nearly in proportion to the rating, except for the 1 000-kw. machine. This machine is of somewhat different design and of closer regulation than the others, and, consequently, if adjusted to the same phase position as the other machines, will take more than its rated share of the load. In other words, it will act as if it were rated 1 200 kw. If desired, it is easily possible to change the phase adjustment, so that when running with the other machines under full load the 1 000-kw. machine will not do more than its proper share of the work. This, however, would mean that under light load and no load its generator electromotive force would lag behind the others, and its action be reversed; that is, the 60-cycle generator would tend to run as a synchronous motor.



DIVISION OF LOAD TWO 500 KW. 40-60 CYCLE SYNCHRONOUS MOTOR GENERATOR SETS (BEFORE CORRECTION)

FIG. 7.

In Figs. 1 and 2, previously referred to, we have considered a set having twice as many poles on the generator as on the motor, such a set as would be used in transforming from 25 to 50 cycles, or from 30 to 60 cycles. With this combination, and the motor connected to the mains, it is apparent that the generator will necessarily have proper phase relations for connection in parallel with generators of similar sets; because every one of the north poles on the generator is directly in line with a pole on the motor, so that no matter which pole of the motor revolves nearest to the reference point *A* the relation between a north pole of the generator and the reference point *A* will be the same. Consider, however, a set working between 25 and 60 cycles. The smallest number of poles possible in this combination is 10 for the motor and 24 for the generator. Fig. 10 represents such a set. A study of this figure will show that there are but two poles on the motor which must stand even with the reference point *A* in order to give proper phase relations on the generator end. Therefore, with one of these sets in service, to connect in parallel a second

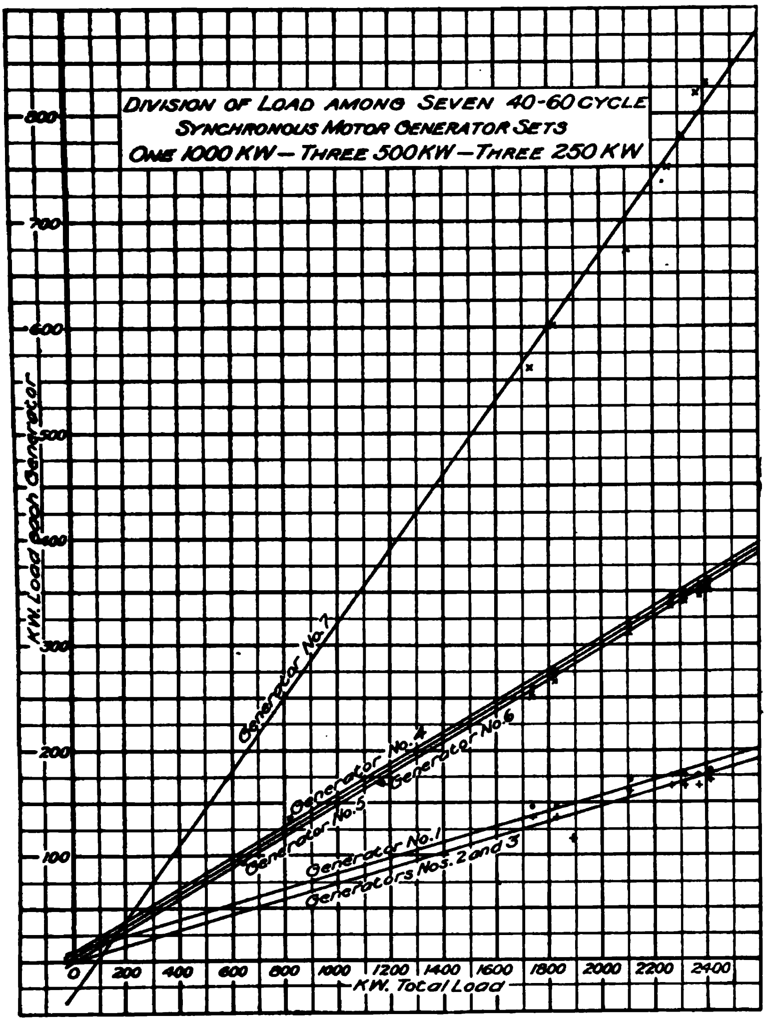


FIG. 8.

set it is necessary to bring one or the other of these two poles to the reference point, the reference point being already determined by the set in service. This means that it is not sufficient to phase the set for one end only, but it must be phased for both motor and generator ends simultaneously. This may be done by one of several methods, as will be explained under methods of starting.

METHODS OF STARTING.

Synchronous motor-generator sets may be started by applying alternating currents, preferably at low voltage, to either end of the set. With this method there is no need of synchronizing as the term is ordinarily applied. It is, however, essential in some cases to make further manipulation to secure proper phase relations.

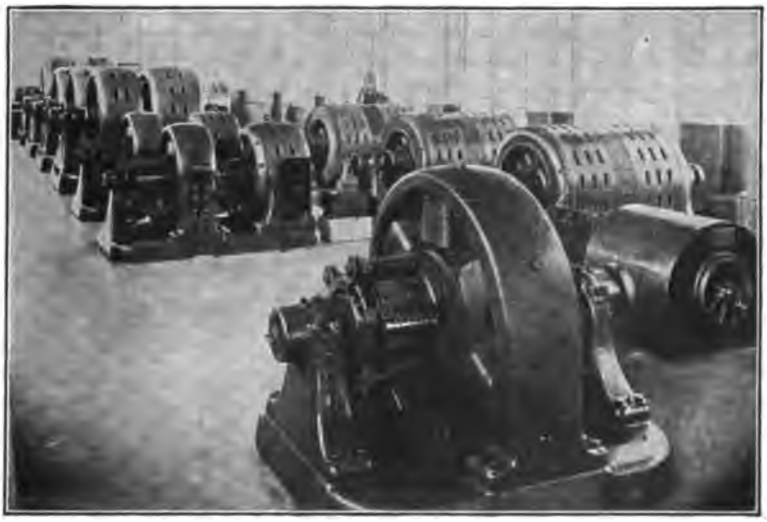


FIG. 9.—Sychronous Motor-Generator Sets, with Exciters. Motors, 40 cycles, 10,000 volts; Generators, 60 cycles, 2,300 volts.

Many of these sets are provided with direct-connected exciters, and in some cases these exciters are used as starting motors. Another combination is the use of an induction motor connected to the set, and provided for the specific purpose of starting. Either of these last two methods requires synchronizing, and, as explained above, in some cases special or additional manipulations to obtain proper simultaneous phase relations.

In order to secure proper phase relations at both ends of the set, the Chicago Edison Company makes use of a special synchronism indicator with two hands appearing on the same dial. The 25-cycle synchronous motor is started by means of alternating current applied to its windings, and after synchronous speed is reached the 60-cycle end has one chance in five of being correct for connecting in parallel with other sets already in service. The position of the 60-cycle hand on the synchronism indicator shows whether or not the phase relation is correct. If incorrect, the switch supplying the synchronous motor is opened and the set begins to slow down; the two hands of the synchronism indicator begin to revolve at different speeds, the 60-cycle hand making 2.4 revolutions for each revolution of the 25-cycle hand. There is one instant when both hands will appear at the top of the dial at the same time, indicating proper phase relations for both machines; at this instant the operator closes the switch on one machine, and as soon as the

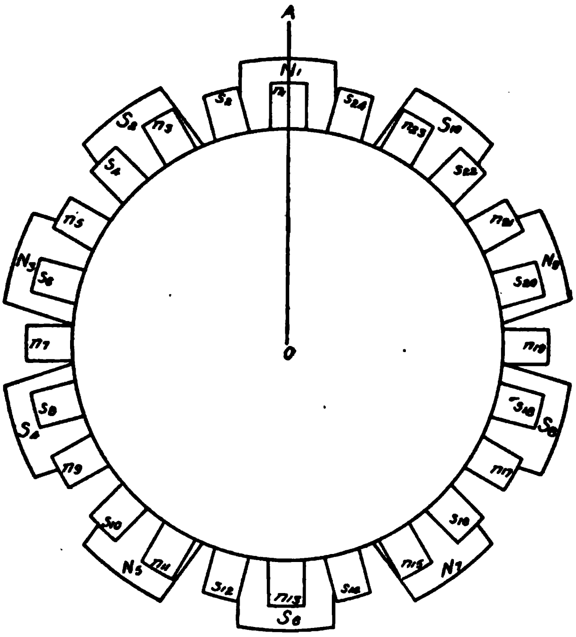


Fig. 10
Synchronous Motor 10 Poles 25 Cycles
Generator 24 Poles 60 Cycles
300 R.P.M.

switch on the other machine is also closed the set is in parallel with those already in service, and takes its proper share of the load.

Similar sets at the Amsterdam sub-station of the Fonda, Johnstown & Gloversville Railway Company are started by means of alternating current at approximately one half the line potential, 13 200 volts. In this station transformers supplying synchronous converters are incidentally used as compensators, to obtain the half-voltage for starting the synchronous motors of the lighting sets. When the set has reached synchronous speed, however, a different method from that employed at Chicago is used to obtain proper phase relations on the 60-cycle generator.

Referring again to Fig. 10, it will be seen that there is one chance in five of the generator potential being in phase with the bus-bars. Phasing lamps and voltmeter connected between the incoming generator and the bus-bar show whether or not the phase relation is correct for connecting in parallel. If this phase relation is correct the voltmeter reading is normal and the lamps burn at normal brilliancy. Any one of the other four possible phase relations will, however, give a different reading on the voltmeter and only partial illumination of the phase lamps. A double-pole, double-throw reversing switch in the circuit of the synchronous-motor field is employed to step the motor back one pole successively at a time until the generator stands in the same phase relation to the bus-bar or to the machine, or machines, already in service. As stated previously, each pole of the motor corresponds to 2.4 poles on the generator, which is equivalent to one complete cycle and 72 degrees additional. As stated above, there is one chance in five that the generator potential will be in proper phase, in which case this stepping back, or " slipping " of the motor will be unnecessary. As it is purely a matter of chance which one of the five phase positions exists at the generator, it will usually be necessary to reverse the motor field successively two or three times; in the worst case it will be necessary to reverse the motor field four times in succession. After the correct phase position has been obtained the generator may be connected to the bus-bars, and the set will take its share of the load.

The same method is followed by The Milwaukee Electric Railway & Light Company. Synchronous motors are started by means of compensators. A 60-cycle synchronism indicator shows which of the five phase positions obtains at the generator. One of these positions is correct for parallelling, and the remaining four points are marked 1, 2, 3, 4, indicating the number of times that the motor field-switch must be reversed..

The sequence of operation in placing a set in service in this manner, is then as follows:

1. Close the oil-switch connecting the synchronous motor to half voltage taps on compensator transformers.
2. When the motor has reached synchronous speed, excite the fields of both motor and generator.
3. Reverse the field of the synchronous motor—unless the generator happens to be in proper phase—until the indicating devices show that the correct position has been obtained.
4. Transfer the synchronous motor from the half-voltage taps to the 25-cycle bus-bars; this is done by means of a double-throw switch, or its equivalent of two separate switches mechanically or electrically interlocked.
5. Connect the 60-cycle generators to the bus-bars.

The mode of operating this combination has been described in detail, as the method is general and may be applied to sets having any combination of poles, speeds, and frequencies, although for those sets in which the ratio between motor poles and generator poles is a whole number, the generator phase relations must of necessity be correct. For certain other combinations in which there is one chance in two of the generator polarity being correct, a field-reversing switch on the generator serves quite as well as one on the motor, and slightly simplifies the operation. Furthermore, in certain special combinations of poles, field-reversing switches on both motor and generator may be employed, this combination reducing the number of times that the motor field must be successively reversed to bring the generator to its proper phase position.

Obviously, in those cases where the sets are started by such means as direct-connected exciters or induction motors, we may use either a double synchronism-indicator, connecting either motor or generator to the bus-bars at the instant when the indicators show proper phase relations for both machines, or we may merely synchronize the motor by the ordinary methods, and then obtain proper phase position for the generator by suitable field-reversing switches.

TABLE I.

DATA ON SOME SYNCHRONOUS MOTOR-GENERATOR SETS.

	CYCLES.		PHASES.		POLES.		Speed rev. per min.	Ratio of frequencies	Chance of gen. phase coming right when started by syn. motor
	Motor	Gen.	Motor	Gen.	Motor	Gen.			
I	25	125	3	3 or single	2 4	10 20	1500 750	5	Certain
II	16⅔ 25	66⅔ 100	3	3	2	8	1000 1500	4	Certain
III	16⅔ 25	50 75	3	3	2	6	1000 1500	3	Certain
IV	25	62.5	3	3 or 2	4 8	10 20	750 375	2.5	1 in 2
V	25	60	3	3	10	24	300	2.4	1 in 5
VI	25	60	3	2	10	24	300	2.4	1 in 5
VII	25	58⅓	3	3	6	14	500	2.33⅓	1 in 6
VIII	25 30	50 60	3	3	2 etc.	4 etc.	1500 1800	2	Certain
IX	33⅓	60	3	3	10	18	400	1.8	1 in 10
X	35	60	3	3	14	24	300	1.714	1 in 7
XI	25	40	3	3	10	16	300	1.6	1 in 5
XII	40	60	3	3	4 8	6 12	1200 600	1.5	1 in 2
XIII	25	35	3	3	10	14	300	1.4	1 in 10
XIV	25	33⅓	3	3	6	8	500	1.33⅓	1 in 3
XV	25 50	30 60	3	3	10	12	300 600	1.2	1 in 5
XVI	25	25	3	single	4	4	750	1	Certain
XVII	25	16⅔	3	3 or single	6	4	500	0.66⅔	1 in 3
XVIII	40	25	3	3 or single	16	10	300	0.625	1 in 16
XIX	60	25	3	3 or single	24	10	300	0.416+	1 in 24
XX	60	24	3	3 or single	10 20	4 8	720 360	0.4	1 in 5

TABLE I.—*Continued.*

DATA ON SOME SYNCHRONOUS MOTOR-GENERATOR SETS.

	REVERSING FIELD-SWITCH.		Number of phase positions and number of degrees apart by changing connections.		Maximum error in construction not eliminated by changing connections.
	Used on synchronous motor to give correct phase by slipping poles successively.	Used on Generator.	No.	Degrees.	
I	....	......	6	60°	30°
II	....	......	6	60°	30°
III	....	......	6	60°	30°
IV	....	yes	12	30°	15°
V	yes	......	30	12°	6°
VI	yes	......	20	18°	9°
VII	yes (yes)*	...... (yes)*	18	20°	10°
VIII	....	......	6	60°	30°
IX	yes (yes)*	...... (yes)*	30	12°	6°
X	yes	......	42	8.57°	4.29°
XI	yes	......	30	12°	6°
XII	....	yes	12	30°	15°
XIII	yes (yes)*	...... (yes)*	30	12°	6°
XIV	yes	......	18	20°	10°
XV	yes	......	30	12°	6°
XVI	....	......	6	60°	30°
XVII	yes	......	18	20°	10°
XVIII	yes (yes)*	...... (yes)*	48	7.5°	3.75°
XIX	yes (yes)*	...... (yes)*	24	15°	7.5°
XX	yes	......	30	12°	6°

* For these sets field-reversing switches on generator, as well as on motor, reduce the number of "slips" required to give correct phase relations.

TABLE OF DATA ON SYNCHRONOUS MOTOR-GENERATOR SETS.

The accompanying Table 1 gives the data on some synchronous motor-generator sets. There is practically no limit to the number of combinations of frequencies and phases which might be employed; the endeavor has been to make the table representative of machines already constructed, and of a few sets which might be required. The frequencies listed are those in more common use in this country. Obviously, the same data will apply to machines operating between 25 and 50 cycles as between 30 and 60 cycles, etc. It is also evident that the ratio of the number of poles for the two machines of a set determines the special features affecting operation; so that it is immaterial as far as this table goes whether a set working between 40 and 60 cycles is made up of a motor having 4, 8, or 12 poles, provided the generator of the set has respectively 6, 12, or 18 poles, etc. It should be noted, however, as a matter affecting the cost of machines, that for a given frequency ratio there is a minimum number of poles; for example, it is a physical impossibility to construct a set for working between 25 and 60 cycles with less than 10 poles on the motor, giving 24 poles on the generator.* Such a set, therefore, must necessarily operate at 300 rev. per min. In the smaller sizes this speed means a machine of more cost than one of the same kilowatt output with fewer poles and operating at a higher speed. For this reason, where it is not deemed essential to have the exact ratio of 25 to 60 cycles, the combination of a 4-pole motor with a 10-pole generator, which gives 62.5 cycles, is frequently used. In some cases, for reasons of engine regulations, etc., it is desired to have a frequency under, rather than over, 60 cycles; in this case a set having a 6-pole motor and a 14-pole generator is used, which supplies 58⅓ cycles, with 25 cycles on the motor.

Table I gives the number of cycles, phases, poles, and rev. per min.; the ratio of motor frequency to generator frequency; the chance of the generator phase relations being correct for parallel connection when the set is started from the synchronous motor; the proper equipment of field-reversing switches when this method of securing correct phase relations is to be used; the possible number of phase positions at the generator by using all the different combinations of con-

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*An "inductor alternator" type of set might have 5 and 12 poles.

nections on both machines of importance when the set is installed, but once the proper connections have been made, should not be confused with the column giving the number of chances in regular operation of phase relations being correct on the first trial. The last two columns give the number of degrees of phase between all the different points obtained by combinations of connections, and the maximum possible difference in phase degrees which may be found between the generators of two sets—due either to different manufacture, or to mistakes and errors in designing, winding, and machining. The number of degrees in this last column is, obviously, one-half the number of degrees in the preceding column.

TABLE II.

PHASE DIFFERENCES AT GENERATOR OF THE SYNCHRONOUS SET.

Motor, 10 poles, 25 cycles, 3 phase, 300 rev. per min. Generator, 24 poles, 60 cycles, 3 phase.

Syn. Motor Field.	Gen. Leads 1-2-3.		Gen. Leads 2-3-1.		Gen. Leads 3-1-2.	
		Gen Field Reversed.		Gen. Field Reversed.		Gen. Field Reversed.
+	0°	180°	120°	300°	240°	60° (420)
—	72	252	192	12 (372)	312	132
+	144	324	264	84	24 (384)	204
—	216	36 (396)	336	156	96	276
+	288	108	48 (408)	228	168	348
—	0 (360)	180	120	300	240	60 (420)

NOTE· No additional positions obtained by interchanging the motor leads; 288° and 216° already obtained.

Order of Motor Leads.	Degrees Motor.	Corresponding Degrees Generator.
1-2-3	0°	0°
2-3-1	120°	288°
3-1-2	240°	216° (576)

The table of data on the above machines might be extended to indicate the connections for each of the different positions. It is thought, however, that if these data are given for a single machine, corresponding figures for any other machine can be worked out with little difficulty. The set chosen to illustrate this is the 10-pole — 24-pole combination working between 25 and 60 cycles: see Table II. Assuming that the generator leads are connected in the order 1-2-3, and the motor leads in the order 1-2-3, the first column gives the phase differences obtained by successively reversing the motor field. Assuming that the phase relation is proper at the outset, a reversal of the motor field would give a phase displacement of 72°, the next reversal 144°, the next 216°, the next 288°, and the next 360°, which is equivalent to zero degrees; or, in other words, we have come round to the second correct position. For each of these phase positions obtained by reversing the motor field there is a corresponding phase 180° removed, obtained by reversing the generator field. This gives the second column of figures, 180°, 252°, 324°, 36°, 108°. If the motor leads, instead of being in the order 1-2-3, are connected in either order 2-3-1, or 3-1-2, for this particular set there will be no additional phase positions obtained; that is, 120° change in phase at the motor by thus interchanging the leads results in 2.4 times as many degrees change at the generator. This is 288°, which, by referring to Table II, is found to be identical with one of the points already obtained by successively reversing the motor field. However, for the generator, changing the leads from the order 1-2-3 to 2-3-1, gives a phase difference of 120°, which is a new phase position, and for this connection we obtain the column 120°, 192°, 264°, 336°, 48°, by reversing the motor field. For each of these phase positions there is the corresponding one 180° removed, obtained by reversing the generator field, giving the column 300°, 12°, 84°, 156°, 228°. Similarly interchanging the generator leads to the order 3-1-2, enables us to obtain the phase positions 240°, 312°, 24°, 96°, 168°, and, as before, for each of these positions by reversing the generator field we obtain the last column, 60°, 132°, 204°, 276°, 348°. Collecting these figures and arranging them in order shows that there are 30 different phase positions differing by 12°.

If a similar table is worked out for each of the sets in the table, it will be found that for some no additional phase positions are obtained by interchanging the motor leads. For other sets the same results are obtained by interchanging the motor leads as by interchanging the generator leads. It is, therefore, immaterial with such sets which machine is selected for making the changes.

Still other sets give a different series of figures for changes in the motor leads from the figures obtained for changes in the generator leads.

As an example of the method of using this table let us follow through set VII for working between 25 and 58⅓ cycles, both the generator and the synchronous motor being assumed as three-phase machines. See Fig. 11. The number of poles is 6 for the motor and 14 for the generator, requiring the set to run at a speed of 500 rev. per min. The ratio of the poles, also the frequency, is 2⅓. If started from the synchronous motor, there is one chance in six that the generator will be in proper phase relation for parallel connection to the other sets. The proper phase relations must be obtained by a field-reversing switch on the motor, five reversals being required in the worst position. If a field-reversing switch is also provided for the generator, but two reversals of the motor field will be necessary in the worst positions.

FIG. 11.—Synchronous Motor-Generator Set with Direct-Connected Exciter. 300 h.p. Motor, 25 cycles, 3 phase, 6 poles, 500 rev. per min.; 200-kw. Generator, 58⅓ cycles, 3 phase, 14 poles.

The combinations of generator and motor main lead and field connections with this set give 18 phase positions on the generator, each 20 degrees apart. Therefore, if it is found that there is a phase difference between two generators greater than 10°, the best combination of connections has not been made, and this point should be attended to before any mechanical changes are made. When the phase difference has been brought down to 10°, or less, if this difference is found to affect the division of load appreciably, any further change must be something that will affect the mechanical relation of one machine with respect to the other. If the difference is small, this may be accomplished by means of changing the shims under the machines, large differences being corrected at the coupling, in case there is one, as in Fig. 12; or on some of the later machines designed for this purpose, by rotating the stationary element the required number of degrees. Such an adjustable set is shown in Fig. 13.

DIVISION OF LOAD WITH PHASE DISPLACEMENT.

Fig. 14 shows the interchange of load between two similar 500-kw. sets working between 25 and 60 cycles. This curve gives the wattmeter readings, showing interchange of load between the two 60-cycle machines when connected in parallel with a given phase displacement. The 30 different phase positions were obtained by changing connections, as outlined previously. The wattmeter readings were obtained from polyphase instruments, and during the test the excitation of the synchronous motor was held so as to keep the power-factor indicator at 100%; the generator voltage was held at normal, 2 300 volts, by changing field excitation as required by the load. It will be seen that the curve does not cross the base line at zero degrees, these being machines which have been referred

FIG. 12.—Synchronous Motor-Generator Set with Shaft Coupling. Motor, 25 cycles, 3 phase, 8 poles, 375 rev. per min.; 400-kw. Generator, 62½ cycles, 2 phase, 20 poles.

to in another part of the paper as having an initial phase displacement, due to slight errors in machining, of approximately four degrees.

MISCELLANEOUS.

Where a number of synchronous motor-generator sets are operated from the same exciter bus-bars, a reversal of exciter polarity will affect all the sets in the same manner, and hence will give no trouble. It should be noted, however, that when the machines are provided with individual direct-connected exciters, or when two or more sub-stations are operated in parallel, a reversal of one exciter may seriously interfere with the ability to connect this machine, or the entire sub-station in parallel with others. This point, like many others in connection with these sets, does not hold for all the different combinations of frequencies; but, unless borne in mind and understood, may be a source of sudden inability to make use of a machine for carrying the load.

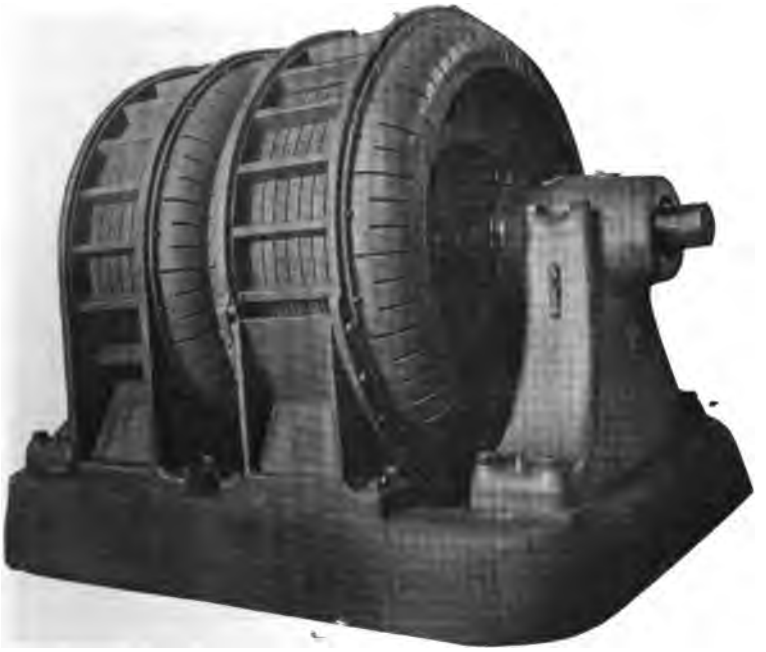


FIG. 13.—Synchronous Motor-Generator Set. Stationary Armature of Motor is Adjustable. Motor, 40 cycles, 3 phase, 12 poles, 400 rev. per min.; 1000-kw. Generator, 60 cycles, 3 phase, 18 poles.

It has been previously noted that the generator of a set, before connection to the bus-bars, has a terminal electromotive force in advance of the bus-bars, or machines already under load. This means that with the usual method of procedure,

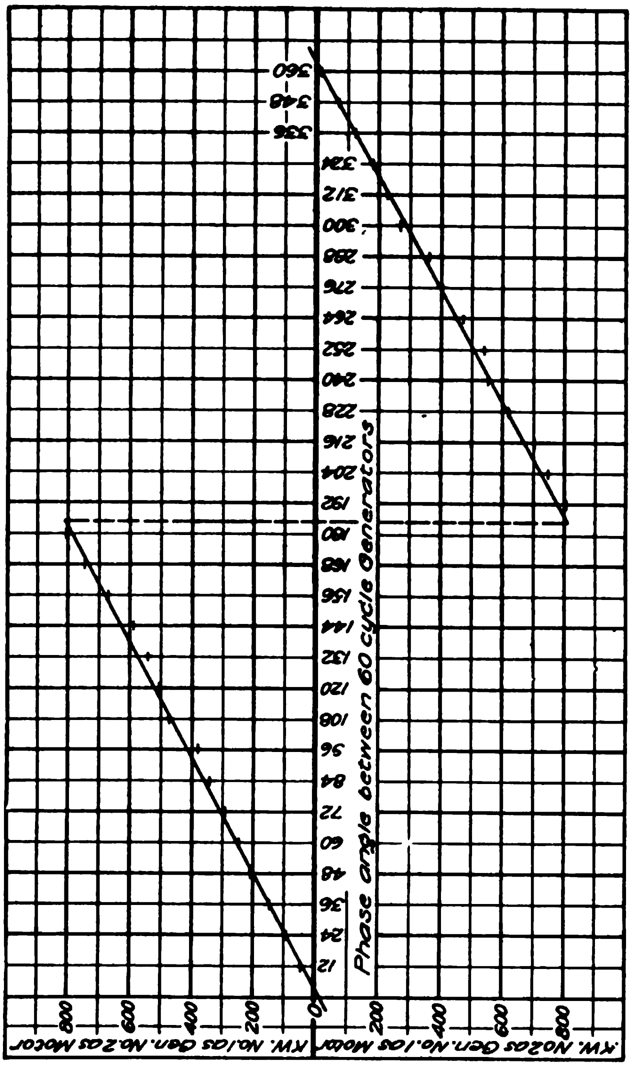


Fig. 14.

at the instant of connecting the machine to the bus-bars, it has a tendency to take momentarily more than its share of the load. In practice, however, this is not found to be a serious objection, although it might be obviated in various ways;

for example, a reactive coil in the motor leads would allow sufficient phase difference between the motor bus-bars and the motor itself to give the same phase relation at the generator terminals as at the generator bus-bars. After connecting the generator to the bus-bars the reactance can be gradually cut out; or, if left in, could be used to permit a change in division of load by adjusting the motor-field excitation. If the generator is connected to its bus-bars before the motor is connected to *its* bus-bars, the set will settle down to its proper division of load by the reverse process; that is, instead of first taking more than its share of the load and then settling down, the generator will, for a short interval of time, act as a motor and gradually assume its proper load as a generator. It should also be noted that there will be a given excitation for an incoming generator, which will give a minimum disturbance on the system, and this excitation having been found experimentally, there should be no appreciable flicker in the lights while connecting the new machine.

TABLE III.

Effect of Changing Excitation Of Synchronous Motor on Division of Load.

Total Load.	MOTOR-GENERATOR NC. 5.		MOTOR-GENERATOR NO. 6.	
	Power-factor at Syn. Motor.	Load on Generator.	Power-factor on Syn. Motor.	Load on Generator.
880 kw.	1.00	440 kw.	1.00	440 kw.
872 kw.	0.90 weak field	397 kw.	0.96 strong field	475 kw.
873 kw.	0.95 strong field	486 kw.	0.90 weak field	387 kw.

An interesting condition that might arise with sets in which the ratio of frequency is quite large, would be a phase displacement of 180° or more between the set under load and the set under no-load. This might occur with a set operating between 25 and 125 cycles; as an angular lag of 30° on the motor end would mean 150° on the generator end, and an additional angle of 30° in the generator itself would give 180°. Under these conditions it would be impossible properly to parallel the set under no-load with the set carrying a load, except by some manipulation which would reduce the angle to less than 180°. One way of accomplishing this would be to connect an artificial load on the set to be placed in service.

Some change in the division of load between sets may be effected by changes in excitation of generator, or motor, or both. Such means of securing division, however, is not to be recommended; it is done at the expense of leading or lagging currents, with consequent increased heating losses.

Table III shows the effect on division of load between two similar 500-kw. sets as a result of changing the excitation of synchronous motors, The stronger the field of the synchronous motor the less will be the angular lag for a given load, and. consequently, increasing excitation of the motor tends to make the set carry more than its share of the load.

The present general tendency toward extension and consolidation means that more and more systems will touch and overlap their neighbors, which may have started at different frequencies. We can, therefore, look for an increasing use of the synchronous motor-generator set.

Discussion on "Some Features Affecting the Parallel Operation of Synchronous Motor-Generator Sets," at New York, March 23, 1906.

W. L. Waters: In the operating of synchronous motor-generators, my own experience has, unfortunately, not shown quite such simple results as those indicated by Mr. Taylor. One installation of synchronous motor-generators will work very well, the machines will divide their load properly, and the load can be changed from one machine to another by means of the field rheostat; while another installation which is apparently very similar will give considerable trouble, even after the machines are lined up and the connections correctly made. Suppose a 500-kw. machine is running on full load and a second machine is thrown in, then this second machine might take 40% of the load or it might take 60%; and as further load comes on the machines, it may be divided proportionately between them, or it may not. The results obtained from the machines seem to be different every time the machines are thrown together. The reason for this is not particularly clear, but it has been suggested that the explanation is to be found in the different condition of the outside circuit and of the load at the time. Most of these machines carry a load which is by no means balanced. The distribution system being three single-phase circuits rather than three phase. The result of this is that there may be very bad conditions of unbalancing, both of load and power-factor, between the different phases, and that these conditions may vary widely from time to time.

Referring to Mr. Taylor's vector diagrams, it will be noticed that he considers that the effect of the internal reactions in an alternator can be represented by a single vector whose magnitude is proportional to the current in the armature, and independent of the phase of that current. Referring specifically to Figs. 3 and 4, this means that the vector " inductive and demagnetizing drop " is constant in magnitude, and independent of the power-factor of the load. This is a pure assumption, and this assumption may possibly explain some of the peculiar results mentioned above. Mr. Taylor's assumption is equivalent to the statement that if there are two alternators for which the angle (β) is the same on unity power-factor, then it will be the same for these two machines on all power-factors, This, I think, is by no means always the case. Assuming, then, that this is not necessarily true, we have at once an explanation of the apparently contradictory experimental results mentioned above. And we can say that though two synchronous motor-generators may divide their load perfectly on a balanced load of unity power-factor, it does not necessarily follow that they will distribute their load so well when that load is unbalanced and of a lower power-factor.

Mr. Taylor points out the important fact that when two synchronous motor-generators are thrown together, they are not strictly in phase; by the synchronoscope, the incoming machine is shown to be leading. The station operator often thinks that this difference in phase results from the machines not being correctly set up, and that this is the cause of some of the peculiar results obtained. The way to find out whether the machines are set up and connected correctly is to parallel them on no load; in that case, with correct motor excitation, there should be no difference in phase.

Referring to the starting of these machines, I think the old method of reversing the field of the motor is unnecessarily severe on the machines. Though modern machines will stand this without damage it is always poor practice to put any unnecessary strain on any machine. I think Mr. Taylor's method of using a synchronoscope with two pointers is much superior.

I think that the subject of synchronous motor-generator sets is still one in which practical results are more valuable than theoretical explanations, and this paper, though perhaps not exhaustive, will certainly give something standard to work from in the future.

J. B. Taylor: Mr. Waters objects to the use of a reversing-field switch in connection with a synchronous motor. I think a little consideration will show that this objection is not valid. Every synchronous motor must go through this process of " slipping " at times; that is to say, it locks in synchronism, and when the field is excited there is one chance in two that the motor will slip a pole.

Furthermore, in the practical operation of a synchronous motor-generator set the slipping is done while the set is connected to the starting taps, so that the increase in current and strain on the machine is not great. Since every synchronous motor must slip at times, and this method of phasing means that the motor may have to slip two or three times in succession, it will not hurt the motor, as it must be constructed so that it will stand the work year in and year out.

A paper presented at the 205th Meeting of the American Institute of Electrical Engineers, New York, March 23d, 1906.

THE RELATION OF LOAD-FACTOR TO THE EVALUATION OF HYDROELECTRIC PLANTS.

BY S. B. STORER.

The value of any water-power plant is due primarily to its earnings, with earnings dependent on the market for its output, and secondarily to the type and quality of the apparatus installed and of the development as a whole. In the case of plants that are in process of development, or that are only partly loaded, the value is, of course, more or less of a speculative nature, and is estimated on the basis of possible and probable income. Prospective earnings as well as actual earnings necessarily rely on selling an amount of power equal to the maximum or the ultimate capacity of the development; and the number of hours per day during which the maximum capacity can be utilized is a definite factor in deciding the price at which the power is sold. This is equivalent to saying that earnings depend on the load-factor, where that is considered as the ratio between the average output of the station and its rated capacity. Carried to the extreme, zero load-factor means no market for the power and consequently no value to the plant. The type or class of installation, whether good, bad, or indifferent, does not affect such valuation, for the reason that the plant represents nothing as to earning power.

Few large hydroelectric plants exist to-day the values of which are not to a considerable extent speculative or problematical, owing to their operating at an output somewhat below their rated or their ultimate capacity. In some cases it has been so difficult to find a market for power that plants have passed through reorganizations with a resultant heavy loss to investors, and still are unable to show any profit or even to pay operating expenses, though power may be offered at rates so low as to be ridiculous when compared with the cost of generating it from coal or gas. No large water-power development succeeds in marketing its output except through a reduction in its selling price to a point very much below that at which it could be produced from coal. Generally the load is obtained from a combination of low-priced power at the generating end with an additional load obtained by transmitting some distance to a market that will bring a higher price. At other plants the entire output is carried a long distance before a suitable market can be found. In both instances the cost of transmission lines and attendant apparatus should be added to that of the power-house development, and included in the cost of the plant as a whole; this may raise the price of power to such a point as to render it non-competitive with power produced by steam or by gas.

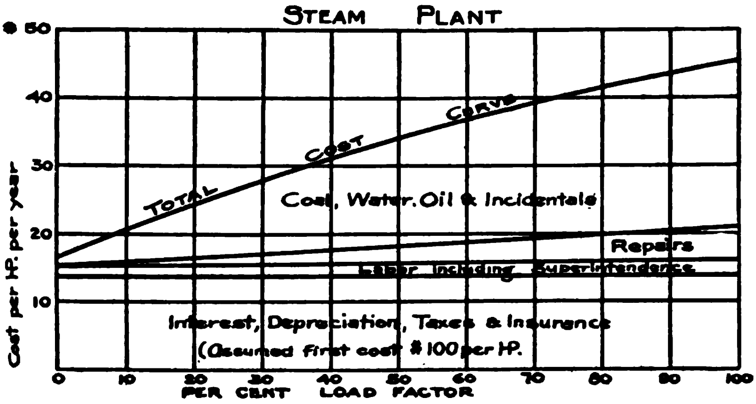


FIG. 1.

This is particularly true of factories having low load-factors, due to operating only 8 or 10 hours a day, and in such cases the necessary income can only be obtained through the sale of surplus power during the hours when the load is below the rated output of the power house. Similar conditions are well known, as they have been faced by every large water-power company. It will generally be found that the most successful plants commercially are the ones that have the highest load-factor. The ideal load is one that remains constant throughout the 24 hours, the plant consequently putting out every kilowatt-hour within its capacity. Any water-power plant loaded in this way can sell power at a price very much below its cost when produced by steam, and still leave a good margin of profit on the investment.

It is generally conceded that the only object in developing a water power is to generate electrical energy at a cost much below that of generating it in any other way, and users of power are so well educated to this fact that they will not buy hydroelectric power unless the saving effected is considerable. It must be much more in fact than that for which they would, for any other purpose, make an expenditure several times as great as that necessary to replace other prime movers.

Comparing the cost of generating hydroelectric power with that from coal or gas is somewhat difficult, but the general method to be followed is shown graphically in the curves given herewith. Figs. 1 and 2, are made respectively for both steam plants and hydroelectric plants, and show the cost of production per horse power per year with relation to load-factor. In neither of these cases is the value given from an actual installation, but is merely an approximation indicating the general conditions as they might exist in any well-built power house of a rated capacity of from 5 000 to 50 000 horse power. The principal difference between the two curves is due to the introduction of the variable items of coal, water, and labor in the steam plant, while the fixed charges in both cases form the base of the area included under the curve. As usual, the fixed charges include interest, depreciation, taxes, and insurance. With hydroelectric plants, the operating expense is so nearly constant as also to become practically a fixed charge. The item of repairs is really the only variable

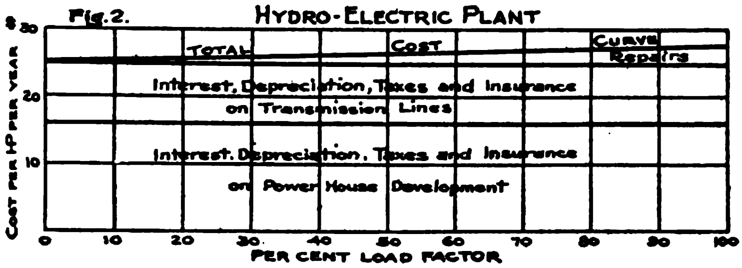


FIG. 2.

in the curve, this generally being considered as increasing in direct proportion to the load-factor.

By superposing the two curves, as shown in Fig. 3, it will be seen that in this assumed instance they cross each other at 23% load-factor, the cost per horse power per year being identical at this point. At load-factors less than 23%, the steam plant has the advantage, and hydroelectric power must be sold at a loss in order to be competitive. At all load-factors above 23%, however, the advantage lies with the hydroelectric plant. The relative value of the two may be obtained by considering the variables—coal, water, and labor—of the steam plant as the equivalent at any given load-factor, of a fixed charge, and by capitalizing this at a rate that will include interest, taxes, and depreciation, and adding it to the first cost of the steam plant we can thereby obtain an approximate value of the hydroelectric development.

Fig. 3.

Making the comparison in another way, the water operating the hydroelectric plant can be made a variable following the line taken by the coal of the steam plant, and by capitalizing the difference between the two curves an approximate value of the potential energy of the water can be obtained. Due consideration must be given to the fact that at load-factors of less than 23% this capitalization is negative and must be taken from the actual cost of the plant, so that it is only at load-factors above 23% that it has any real value. In addition, the curve representing power cost from the steam plant must be discounted by an amount corresponding to whatever reduction must be made in hydroelectric rates to effect its sale.

The conclusion is that in all places where the flow of water is constant throughout the year the load-factor determines the earning power, and hence establishes the value of any plant. Where an intermittent or insufficient supply of water may be stored and used during times of peak-loads, at a rate much higher than the normal flow of the stream, the earning power is not dependent on the load-factor to so great an extent, but such hydroelectric plants are generally of small capacity, adapted for lighting purposes only, and are to be considered as an exception, to which the above method of evaluation will not apply.

A paper presented at the 205th Meeting of the American Institute of Electrical Engineers, New York March 23, 1906.

NOTES ON DESIGN OF HYDROELECTRIC POWER STATIONS.

(WITH REFERENCE TO THE INFLUENCE OF LOAD-FACTOR.)

BY DAVID B. RUSHMORE.

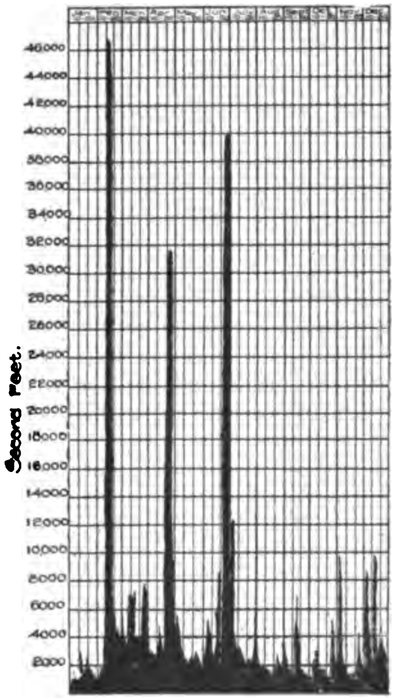
Hydroelectric power plants are designed with the ultimate object of being producers of wealth. All factors which have any bearing on fixed charges, cost of operation, or sale of power, must be considered. At the time of designing, operating conditions cannot be known definitely, and such factors as amount and distribution of load can be considered only in a general way. This is one difference between most water-power and steam stations. When the plant is in operation, conditions of load are constantly undergoing change. It is therefore generally impossible to design a system for fixed conditions, and provision must be made for a certain flexibility of operation and for future growth. Also, costs vary widely in different places and are confidential.

The distinguishing feature of hydroelectric installations is the special character of all conditions and apparatus. Hydraulic conditions: amount of rainfall, drainage-area, run-off, stream flow, storage, head of water, speed of wheels and generators—all these are peculiar to the particular location. Generator and transformer capacities and voltages are always more or less special, while the systems for transmission and distribution of power are invariably so.

Definite values can be considered therefore only with regard to a particular application, and a discussion of the subject must be confined to general principles. The selling price of power is also a variable, depending on the particular location and class of service, and this is the criterion by which the desirability of any development must ultimately be judged.

The two factors of prime importance are reliability of service and commercial considerations. Reliability of service may be obtained from a system all of the separate parts of which do not possess this characteristic; but if the supply of power is unreliable, the sale of power is impossible and no commercial considerations will exist to be considered.

Nº 1



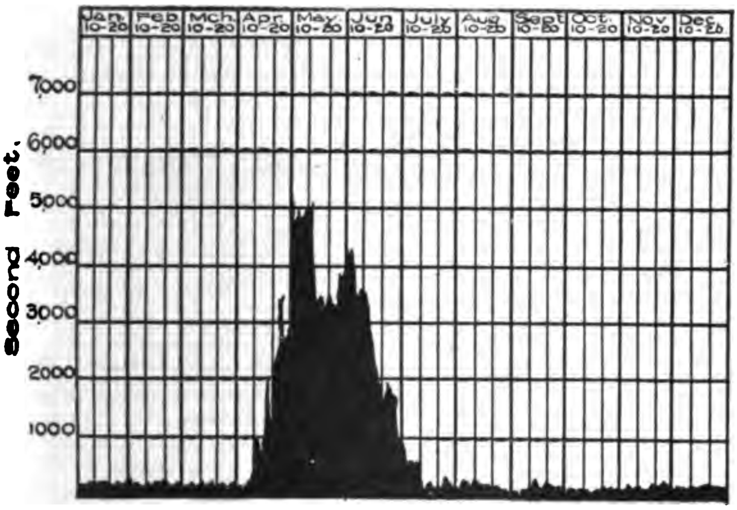
STREAM IN REGION OF FREQUENT RAINS.

FIG. 1.

Duplication of apparatus and isolation of troubles, combined with the best construction and protective devices, are the principles employed to obtain continuous operation. Duplicate ditches, regulating reservoirs, multiple pipe-lines, generator and transformer unit combinations, instantaneous automatic sectionalizing switches, and duplicate bus-bars and transmission lines, together with properly applied relays—are the means used to prevent interruption of service. Additional security is gained where a number of power stations feed into the same transmission network, as in many western systems. In such instances any power house in trouble can be cut off entirely. Steam auxiliaries at the receiving end, supplying part of the load while floating on the system and possessing large overload capacities, as used at Los Angeles and Schenectady, are insurance against disabilities from line troubles.

The modern tendency is decidedly in favor of transferring the charges for maintenance and repairs to the interest column, by adopting more expensive construction with greater margins of safety. This is shown by the substitution of tunnels for flumes and ditches, and of steel towers for wooden poles, which is well illustrated in the new Kern River development of the Edison Electric Company of Los Angeles, where the length of tunnels is three-fourths of the distance over which the water is carried; and, in a country particularly adapted for use of wooden poles, the line is to be carried 115 miles on steel towers. The factor of safety in insulators is also wisely being raised.

Nº 2.



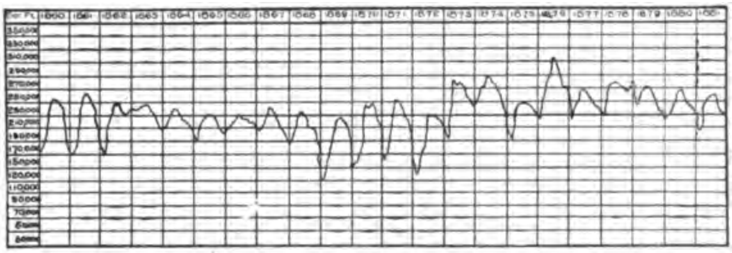
STREAM IN REGION OF CYCLIC RAINFALL.

FIG. 2.

TYPE OF PLANT.

Hydroelectric installations naturally divide into somewhat clearly defined classes, depending upon conditions. The western high-head plant, with great fluctuations in stream-flow and with long ditches and pipe-lines, containing but few units and feeding into a high-tension network, is under different conditions from a low-head, many-unit, single-plant installation delivering power over short distances or to a single point. Reliability of service is not of such great importance in irrigation pumping as it is in the lighting supply of a large town. This is not always recognized in the discussion of comparative advantages of small complications necessary to obtain reliability of service as compared with extreme simplicity and home-made switching apparatus. Conditions which have proved satisfactory under conditions in the West could not be considered for systems which never allow current off the system.

NO 3.



STREAM DISCHARGE OVER A PERIOD OF 21 YEARS.

FIG. 3.

RELATION OF STATION CAPACITY TO STREAM FLOW.

The majority of plants have a rated generator capacity between maximum and minimum stream-flow. As at Niagara, the plants may be below stream-flow at all times, and some developments, especially when replacing steam plants which are held as a reserve, may have a rated capacity of approximately maximum flow. If coal is high, power is dear; if power is cheap, coal is low, so that a steam auxiliary is always desirable if its use will materially increase the amount of power that can be sold.

The number of plants to the system and the distribution of plants on different watersheds materially affect conditions of design and operation. A single plant with all the power transmitted to one place represents the most severe conditions; many plants, widely separated, on different watersheds, with steam auxiliaries and widely distributed use of power, the most favorable so far as load conditions are concerned. The type of construction is different for high and low heads and for few and many units. A peculiar feature of high-head building construction is the omission of openings on the hillside to provide for breaks in the pipe-line which sometimes, though very rarely, occurs.

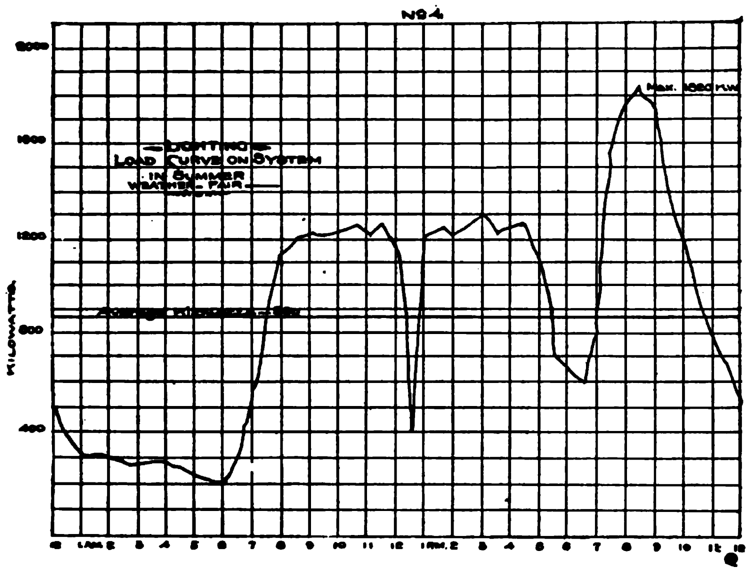


FIG. 4.

The presence or absence of steam or water auxiliaries, and the use of hydraulic or electrical storage, influence distinguishing features in design, such as; 1. rated and overload capacities; 2. number of units; 3. types of wheels; 4. duplication of apparatus; and 5. reserve units.

The class of service has an important bearing on the system of control. Where conditions of contract do not severely penalize trouble, much simpler arrangements can be used than where it is demanded that no expense be spared to insure against interruptions.

Load-Factor and Load Curves.

Upon the exact definition of load-factor there is lack of agreement. It will here be called $\frac{\text{average output}}{\text{maximum output}}$. No definition is satisfactory for all classes of load without explanation. A limit on the time of peak-load or the use of rated capacity considerably modifies the figure obtained.

Commercial loads—nearly always mixed in character—can be divided into railway, lighting, general power, pumping, hoisting, and electrolytic. These have seasonal, as well as hourly and daily, variation. Railway and lighting loads are particularly subject to abnormal variations from unusual causes. Both have large peaks over certain hours, and for a part of the day approach zero load. General power-load has an even curve for nine or ten hours with light load at noon, and is then off entirely or very light. A pumping load may be very steady and continuous over the day. During some seasons the pumps, if employed for irrigation work, may be out of use entirely Fire pumps have a great and unknown

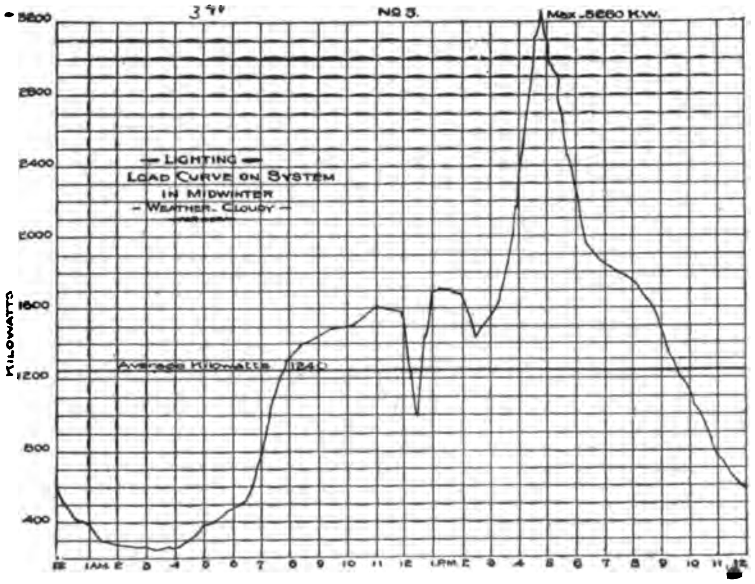


Fig. 5.

load variation but are seldom used but as part of larger loads. Hoisting loads are extremely variable in themselves, but the effect on the system may be smoothed out by use of a large number of hoists, or by the proper adaptation of fly-wheels and methods of control. Electrolytic loads are ideally constant at all times.

Machinery must be installed to carry the peaks; and the determining of the best methods of meeting large load variations constitutes the problem of prime importance in designing water power installations.

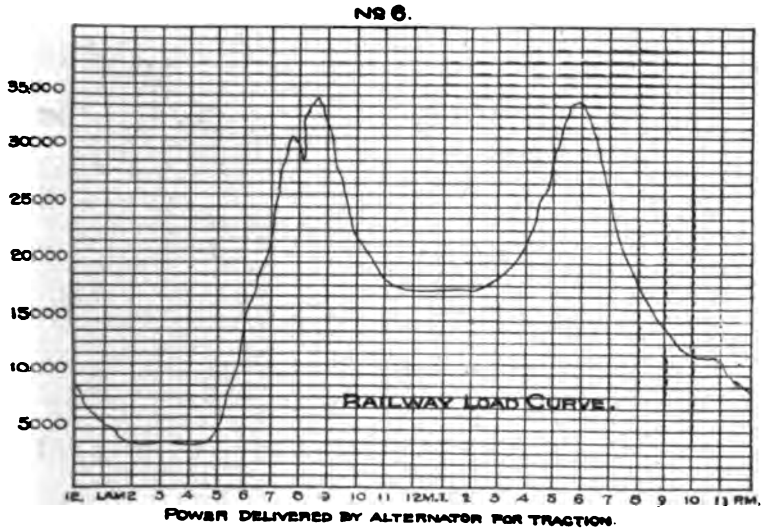


FIG. 6.

HYDRAULIC.

Water supply is extremely variable. The annual rainfall in this country varies from 0 inches to 70 inches. Less than 20 inches gives an arid region, and less than 15 inches requires irrigation. From 0 to 50% of the rainfall may appear as run-off, the remainder going to seepage, evaporation, and vegetation. Run-off may follow rainfall hours or days or months later; in case of snow, depending on the character of country, soil, forests, and vegetation. The percentage of run-off decreases with decrease of rainfall and, under the same conditions, the number of second-feet per square mile per inch of rainfall decreases with increasing area to watershed.

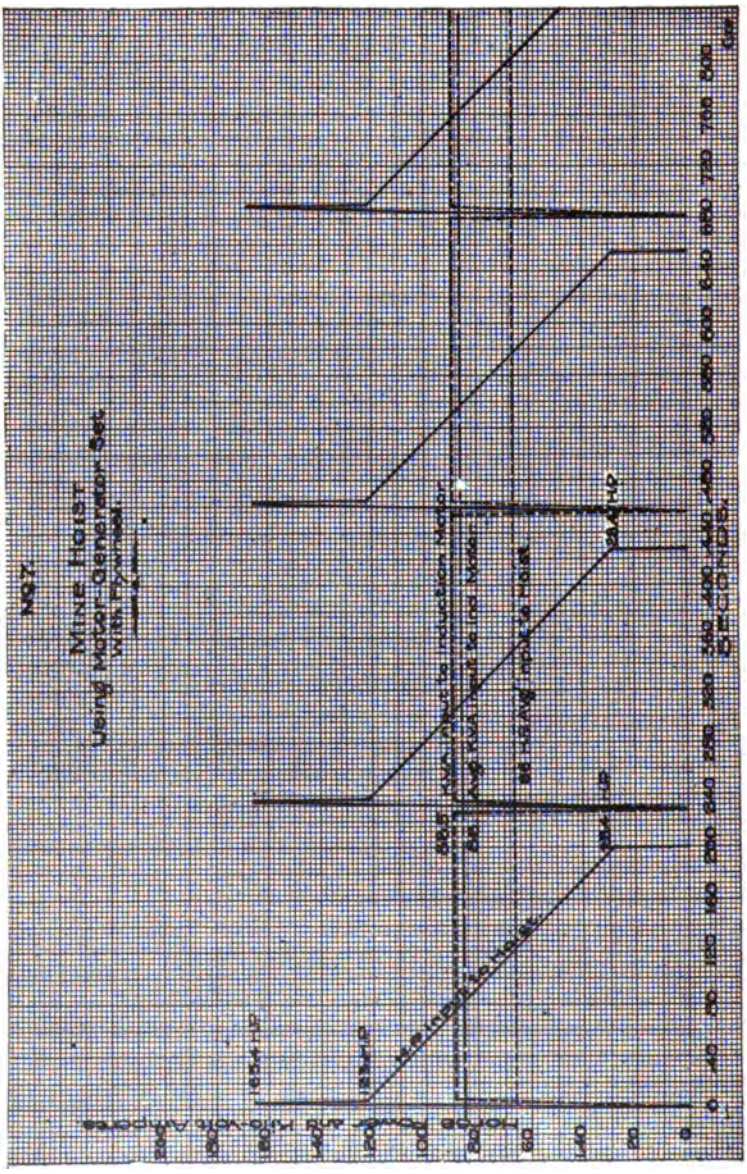

No. 7.
Mine Hoist
Using Motor-Generator Set
With Flywheel.
Horse Power and Kilo-Volt Amperes
Seconds
Induction Motor
Hoist
HP
0
20
40
60
80
100
120
140
160
180
200

FIG. 7.

Stream-flow varies greatly by the day, season, and year, but over a number of years it averages nearly constant. The curve of stream-flow, especially minimum flow, is of prime importance in water-power development. For considerations of storage, the load-factor of stream-flow has a vital bearing on the amount and cost of development. The great problem of hydraulic development is to transform the daily and annual stream flow to correspond to the respective load curves.

The design of different elements is determined by various limits, some of which are but indirectly connected with the load-factor. Water conductors should primarily be of sufficient capacity for the worst conditions—not always the case. The grade of ditches may vary from 40 feet per mile for small ones, to 10 feet or less per mile for large, the allowable velocity depending on the soil. Velocities should be sufficient to prevent the growth of vegetation in ditches, but not sufficient to cause erosion.

The capacity of water for carrying sand, etc., varies as the sixth power of its velocity, and small decreases of velocity cause deposition of suspended matter—a fact made use of in sand boxes. With large quantities of water, it may be cheaper to replace wheels occasionally rather than to remove sand. In one western plant, after a storm, the diameter of a nozzle was cut from 3.5 inches to 4.5 inches in an hour by sand in the water.

Erosion wears away the ditch, with a possible loss of 20% or more in seepage through a stony bottom. Washes frequently break an embankment, the most annoying and expensive repairs to make. Three feet per second is the average figure in many western ditches; and two feet is necessary in some fine soils. This figure is subject to much variation. The loss of head in water conductors might be, but seldom if ever is, proportioned by Kelvin's law. A change in selling price or operating conditions after construction, then, would be followed by mathematical disaster. Ditches, as actually constructed, are usually in exposed places on the sides of steep mountains; they are costly to build and difficult to repair, and velocity of erosion is a limiting feature. It is estimated that California possesses over 5 000 miles of ditches, most of them constructed originally for hydraulic mining. (The plant at Electra has two ditches of 21 and 19 miles length, respectively.)

Velocities in flumes may range from 8 to 20 feet per second;

one flume about 9 feet wide, falls about 7 feet per mile; another 6 feet wide has a grade of from 8.5 to 17.0 feet per mile, depending on the length of section. Tunnels, when lined with concrete, may have a friction-coefficient of from 0.010 to 0.012. The complete cost may vary from $5.00 to $6.00 per cubic yard, or from $20 to $30 per lineal foot, for a 9-foot tunnel.* The coefficient of friction with rough rock walls will be from 0.030 to 0.035. For lined tunnels, 12.5 feet per second is given as a conservative velocity. Velocities much higher are in use in short lengths.

Velocities in pipe lines are limited by considerations of cost, efficiency, safety, and regulation. They vary from 3 to 15 feet per second. Wooden pipes with low velocities are often used at the upper ends, but the greatest loss of head should occur at the bottom in the most expensive pipe. The thickness and factor of safety used increase with the head.

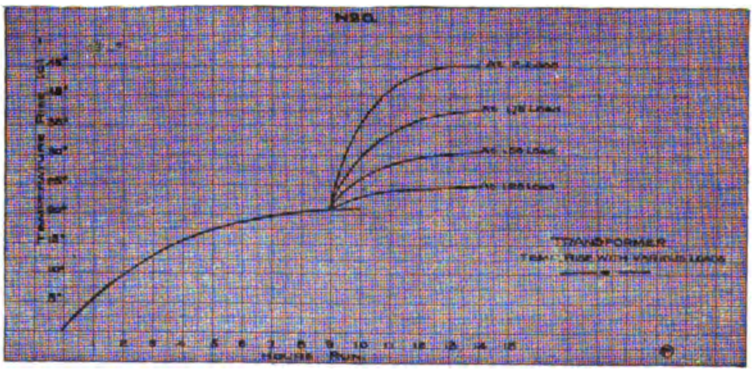


FIG. 8.

For considerations of freight, pipe lines should taper to allow proper packing by nesting. Cast-iron pipe is never now installed, although in use in a number of early plants. For all high-pressure work, riveted sheet-steel pipe is now universally used.

The best type of wheel to be used depends upon the head, quantity of water, speed, and range of load. Turbine wheels are efficient through only a small range of load, and under high heads are not easily regulated. In general, with low heads, large quantities of water and a number of generators to the

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* Proceedings Second Conference of Engineers of Reclamation Service.

plant, turbines are used. For small quantities of water, high-head impulse wheels are employed. Improvement in light-load efficiency and some reserve against breakdown may be obtained by mounting impulse wheels on both ends of the generator shaft.

The use of impulse-wheels of the Pelton type is limited by certain features of design. The centre of buckets should run at about 45% of the spouting velocity. The diameter of the wheel should not be less than ten times the diameter of the jet, and this ratio should preferably be 15 or 18. Also, the number of buckets which can be mounted on the rim has an important bearing.

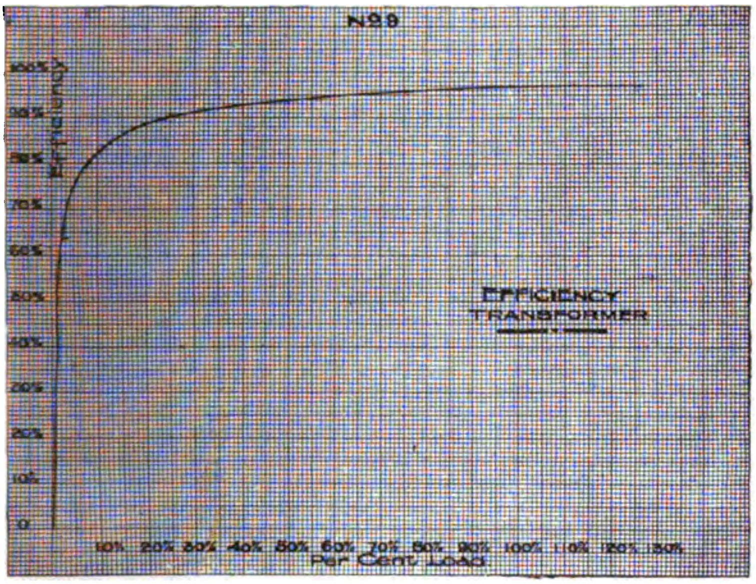

FIG. 9.

The limiting speed of turbine wheels is not so clearly fixed. Turbine wheels are more flexible in design, and present tendencies toward high speeds and large units, as well as their application to higher heads, are having marked effect upon their development. The best type of wheel for a particular installation is not always self-evident. The use of vertical or horizontal types is still a matter of discussion and, under the same conditions, both types are installed, as at Niagara. Horizontal bearings for large high-speed units become abnormal, and certainly the step-bearing has proved its reliability on the steam turbine. Impulse-wheels may be used with vertical shafts and a number of nozzles applied to one wheel. The Necaxa Plant in Mexico is an example of this construction.

Vertical shafts give a better operating room, requiring less space. Generators and, frequently, wheels also are cheaper; bearings are simple and, with single wheels, have many attractive features. Small units, or units where impulse wheels are used, are generally horizontal.

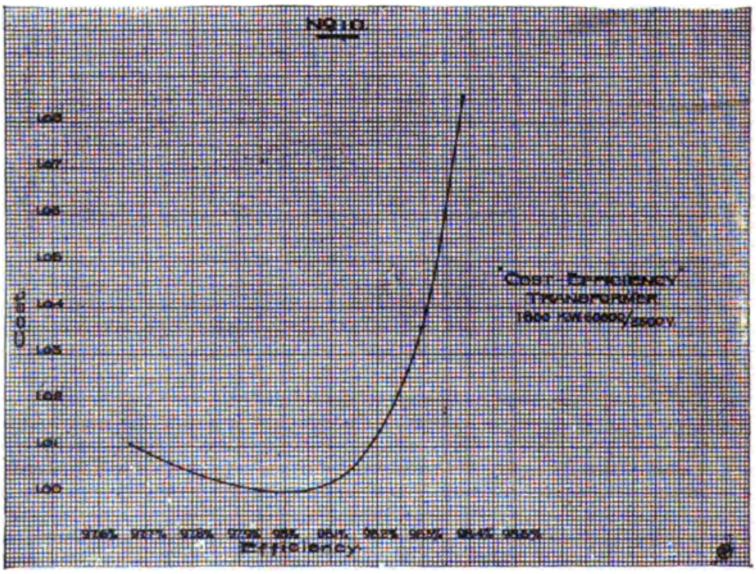

Fig 10.

The number of water-wheels to use with one generator is often a problem in low-head installations. With horizontal units, one or two impulse-wheels may be used and any even number of turbines. Fluctuating heads are always turbine propositions and, as one design of wheel can at a given speed work efficiently through only a limited range in head, a number of wheels on the same shaft, for use at different times, may be necessary. Overloads can be carried by using the other wheels, though inefficiently. The character of the load needs consideration in this regard.

Water-wheel generators have always been designed for 100% increase in speed, an unnecessarily conservative figure. In certain types of plants, subject to line disturbances, generators not infrequently run away. 63% increase in speed has been recorded in some cases. Of course this value depends upon the characteristics of the particular unit.

RATED AND OVERLOAD CAPACITIES.

In no other place is there opportunity for the display of better judgment in the adaptation of a plant to definite assumed load conditions than in the proper subdivision and rating of the elements of plant design. These principal features are reservoirs, ditches, flumes, pipes, wheels, generators, transformers, and lines. The factors especially concerned with the conditions of load are: 1. number of units; 2. the characteristics at different loads; 3. the limiting conditions in the design; 4. commercial considerations of investment; 5. repair and depreciation charges; 6. possibilities for meeting future conditions.

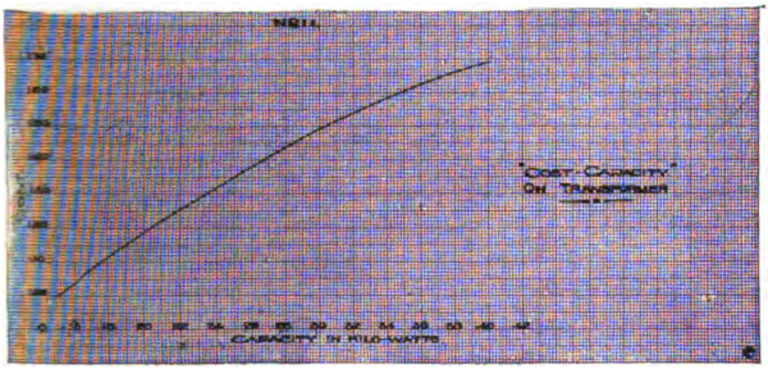

FIG. 11.

For large developments the selection of reservoir sites and capacities requires special investigation. Often several main reservoirs check the river flow, and a regulating reservoir at the head of the pipe-line gives constant ditch-flow and carries the load temporarily in case of accident to the water supply. The cost of storage increases with the head and often decreases at low heads for increasing capacities. If great fluctuations in stream-flow obtain, it is seldom possible, from a commercial standpoint, to store all the water. Where development exceeds minimum stream-flow, there are but few high-head propositions where storage is not desirable; conversely, in many low-head installations the cost of storage is prohibitive.

Ditches, flumes, and pipes all come under the head of water conductors. A number of installations have more than one source of water supply. Erosion in ditches and loss of head in pipes are the usual limits of design. For flumes there is a grade for maximum capacity which, if exceeded, decreases the amount of water that can be carried, by causing a wave motion. The load conditions have much to do with allowable velocities in pipes, which are similar in principles of design to electrical conductors. The loss of head at maximum load is important. High velocities and rapidly varying loads make regulation difficult. A subdivision of the pipe-line is desirable. Pipe-lines for high heads are costly and investment for different arrangements are studied before a final decision is reached. Flumes have a definite, and, at times, a troubled life. Ditches need repairs, but no depreciation charges. With pure water, pipes should show no deterioration if properly protected.

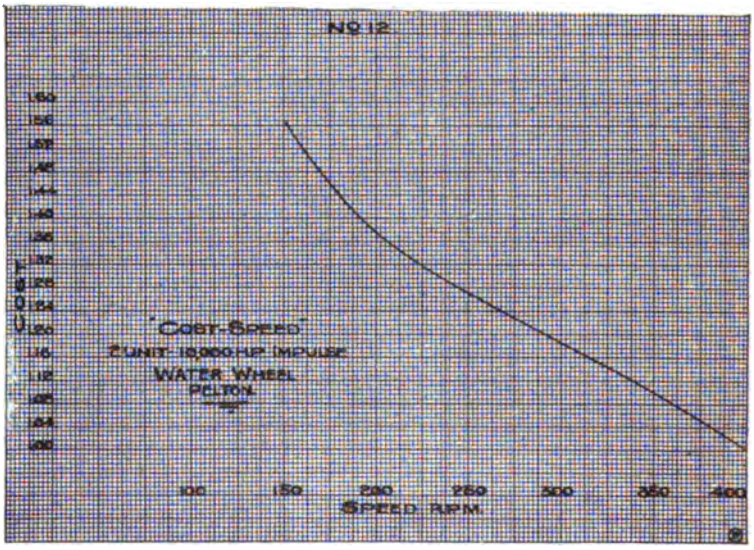

FIG. 12.

Wheels and generators demand careful study to decide the best capacities. The size of the generator is usually indicated by some conditions in the proposition. The loss of one unit should not cripple the service. The generators and wheels should operate at points of best efficiency. The generator and wheel combinations are limited, and speeds are fixed by number of wheels, type, head, and output. For one-plant systems the number of generators is preferably not less than four nor more than eight. For multiple-plant systems, one unit to the station is not uncommon.

When no strong reasons exist for doing otherwise, water-wheel driven generators should have a rating of 40° cent. rise at full load and 8% regulation. This agrees with a wheel rating for 4/5 gate. A greater approach to standard in this is very desirable. This allows for 25% overload on peaks. There is no reason for a higher generator rating if the capacity does not exist in the wheel. A small margin—about 10% of gate—should be left for governing. The above is for a number of units and a time variation of load not greater than can be cared for by placing in operation additional units. For suddenly-varying loads and peaks over short intervals, it may be desirable to have a wheel rating of 100% in excess of generator. The greater the number of units, the smaller this need be. In some cases it is desirable to take the peaks on a

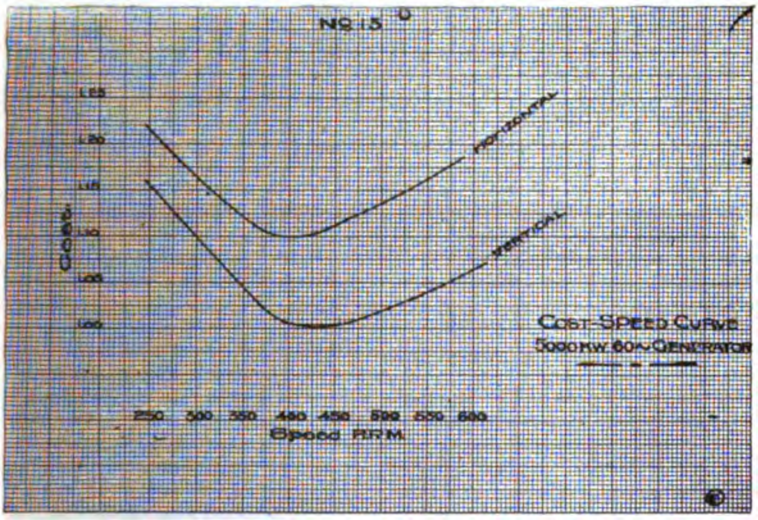

FIG. 13.

part of the station and to block the governors on the remaining machines. Transformer ratings are usually the same as generator, and, when possible to do so, it is often desirable to make one unit of the two.

Generators for a given output have a speed for which the cost is a minimum. Unless peripheral velocities are increased, raising the speed does not decrease the active material. So, when this point has been reached, any further increase calls for mechanical requirements which rapidly increase the cost.

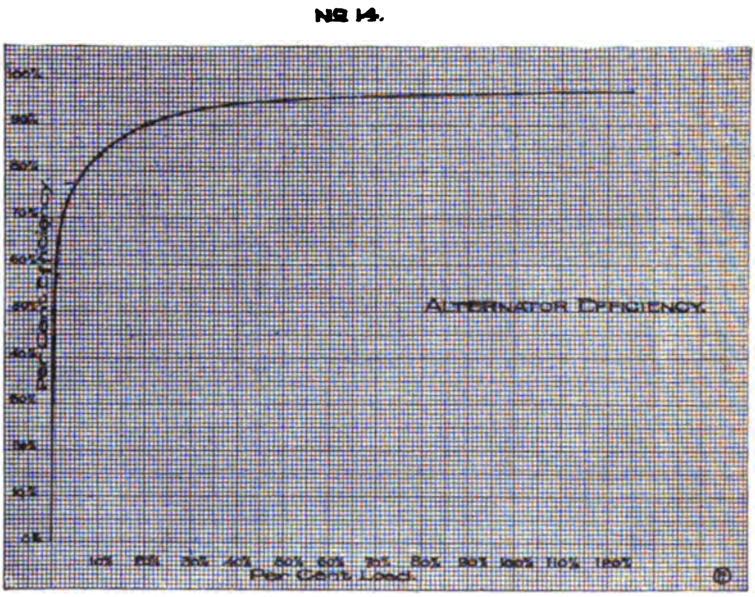

Fig. 14.

Water-wheels, within the limit of generator speeds, decrease in cost with increasing speeds.

Most transmission lines are designed from a standpoint of regulation but occasionally a case arises where an application of Kelvin's law is possible. For low-head factors, average losses may be used. A large number of equations have been developed for this work but an equality of interest on investment and value of lost energy is what is required. Unless maximum developments are installed, ample margins in all hydraulic and electrical conductors should be allowed for future growth. The neglect to do this has adversely influenced many developments.

EFFICIENCIES.

The cost and value of efficiency in power-plant designing is an important but not clearly understood subject. The rough approximation usually made is to compare the selling price of the increased output with the interest charge on the greater cost. Where the saving in energy can be sold, as is usually the case, a higher efficiency in water conductors means a greater output and a greater capacity of installed apparatus with higher total cost, so that the investment charge for the gain in power is greater than usually considered. This is true of all parts of the chain of energy transformation.

Generator efficiency curves are flat beyond half load and are generally slowly increasing at overloads. Above half load, variation in generator efficiency is not of importance. Turbines have, however, a small range of load for best efficiency; while the curve for impulse-wheels is much flatter. Users of electrical apparatus should carefully compare characteristics and costs of different types of machines. Cheapness can nearly always be obtained by the sacrifice of quality.

The cost of efficiency is less susceptible of determination than the value. Water-wheels can be made of the best efficiency by designing them for the special conditions, instead of using standard patterns, and by the employment of a high grade of material with careful finish. The life can be increased by use of expensive metals and by cleaning the water. Wheels probably differ in efficiency much more than electrical apparatus. Doubt simply implies difficulty in hydraulic testing and scarcity of reliable results.

The generator efficiency is improved by using more copper and iron and a higher grade of insulation. Heating or regulation are the limits in design, and efficiency must be good with present types. A cheaper machine can be obtained with greater energy loss, the temperature being controlled by utilizing an increased windage.

Transformer costs may be materially reduced by lowering the efficiency. Low-efficiency transformers are prone to a short life and a hot one, and are, as a rule, much less desirable to operate than to buy. There is a theoretical point in design where the cost increases as the efficiency grows poorer. The efficiency curves of the best transformers are so flat that it is immaterial at what point they are operated.

STORAGE.

With a limited water supply, storage of water determines the possible development. Variations in load occur by the hour, day, season, and year. Auxiliary or regulating reservoirs at the head of the pipe-line take care of daily peaks, keep an even load on the water conductors, and serve to carry the plant over temporary ditch troubles, also serving as sand-boxes. The location of the pipe-line often renders storage at this point impossible. In one case, a flume of large dimensions is used for peak storage. In another, the water supply to a flume several miles in length is cut off entirely and the total stream-flow used for another station.

Main reservoirs are on the river and regulate its flow. If these are of sufficient size, the total run-off can be used. The Reclamation Service is at present doing a great work in water storage, in some cases over a term of years. Snow is a natural form of storage, well illustrated at Puyallup, where with a great variation in rainfall a nearly constant stream-flow is obtained. Forests, vegetation, and the soil fill the function of reservoirs. Dams are built to catch the underground waters.

For suddenly varying loads, as in railway and hoisting work, a fly-wheel is used to provide for instantaneous peaks. Irrigation laws may forbid the storage of water on old ditches. Electrical storage, at the distributing points, bears to the electrical system the same relation that the regulating reservoir does to the hydraulic.

AUXILIARY PLANTS.

The capacity of a water-power installation can usually be largely increased by the use of steam auxiliary plants. A steam plant can supply the deficiencies of stream-flow, can carry peaks in any season. It may act as a regulator with steam turbine floating on the lines, the hydraulic generators running under constant load; it may act as a reserve in case of breakdown on line; and may serve to furnish the wattless current for the system, allowing other machines to carry greater overloads. The turbine unit may be run idle part of the year as a synchronous condenser, or may float on the line as such for part of the day and deliver energy at other times. Contracts for supply of continuous power, with severe penalty clauses, may necessitate the installation of an auxiliary plant at the distributing end of the line. Such a plant is now being installed at San Francisco.

With improvements and reduction in cost and operating expenses of steam generating apparatus, the auxiliary plant becomes of increasing importance and, in some instances, threatens to become the more important.

A form of water-power auxiliary was recently suggested in which the installed generator capacity far exceeds the normal flow of the stream. Water is stored throughout the day and the plant operated for but a few hours on peaks of system.

CURVES.

The curves used to illustrate this paper are intended only to illustrate principles and not to give definite values, and must be so understood. They are considered self-explanatory.

A paper presented at a Meeting of the Philadelphia Branch of the American Institute of Electrical Engineers, Philadelphia, April 9, 1906.

A NEW METHOD OF TURBINE CONTROL.

BY LAMAR LYNDON.

In bringing to your notice a new method of turbine control which will presently be explained, it is necessary to discuss, briefly, the theoretical conditions and from them derive a knowledge of the relative importance of the various factors involved. With this knowledge it is easy to deduce the necessity for certain features of design which have, in this method, been provided.

In the case of a turbine fed by a long, closed pipe, it is evident that any change in the gate opening must be accompanied by a change in the velocity of the column of water, and since this column has weight, velocity, and is practically incompressible, kinetic energy, proportional to its mass and the square of the velocity is stored in the moving water and any change in its velocity must be accompanied by a corresponding change in its energy, which can only take place by change in the internal pressure in the pipe.

Starting with the formula, the basis of mechanics,

$F = M A$, in which
F = Force or pressure in pounds
M = Mass = Weight in pounds $\div 32.2$
A = Acceleration in feet per second;

the change in pressures for changes in gate opening can be deduced.

Let S = Area of pipe in square feet.
L = Length of pipe in feet.
W = Weight of a cubic foot of water = 62.5 lb.

Then $S\,L\,W$ = total weight of water in the pipe at any time

and its mass $= \dfrac{S\,L\,W}{32.2}$ (1)

If C_1 = velocity in feet per second with a given gate opening
C_2 = Velocity with a reduced gate opening
T = Time of change in seconds.
then P the pressure set up will be,

$$P = \frac{S\,L\,W}{32.2} \times \frac{C_1 - C_2}{T} \tag{2}$$

which is the total pressure to retard the mass of water.

If p = pressure in pounds per square inch,

$$p = \frac{P}{S \times 144} = \frac{S\,L\,W}{S \times 144} \times \frac{C_1 - C_2}{32.2\,T} = \frac{L\,(C_1 - C_2)}{74.3\,T} \tag{3}$$

this being the formula for excess pressure, above that due to the head when the gate opening is reduced, or the reduction in pressure to be subtracted from the head at the time when the gate opening is increased. It is to be noted that the pressures per square inch are independent of the diameters of the pipes.

As an example take a pipe 1 000 ft. long; head at the turbine 90 ft.; velocity of water in the pipe 6 ft. per second at full gate. Reduce this opening to 70% gate in three-fourths of a second. The reduced velocity of the water is 70% of 6 = 4.2 ft. per second.

$$p = \frac{1\,000\,(6 - 4.2)}{74.3 \times 0.75} = 32.3 \text{ lb.}$$

The head on the turbine is 90×0.434 = 39 ft. normal. Percentage change in the pressure is $\dfrac{32.3}{39} = 83\%$.

If the gate were moved from 70% to 100% opening as above, the net head acting for the short time of gate movement, would be 39 – 32.3 = 6.7 lb., or about 17% of the normal head.

When the gate is completely closed the phenomena are very different as are the laws which govern them. These will now be investigated.

If the gate were closed instantaneously, the excess pressure set up would be infinite if it were not for the ductility of the conducting pipes and the elasticity of the water itself. Because of these effects, however, the pressures produced by instantaneous closing of the gate are not infinite but, from a theoretical viewpoint, small, though exceedingly great when considered as hydraulic effects, to be taken care of in practice.

For increase of pressure when the valve is closed instantaneously the formula is

$$p = c\left(\sqrt{\frac{\omega E E' t}{g\,(t E' + 2 R E)}}\right) \qquad (4)^*$$

in which

p = Increase in pressure per square inch.

c = Initial velocity in feet per second

ω = Weight of a prism of water 1 ft. long and 1 sq. in. in cross-section = 0.43416

E = Modulus of compressibility of water = 294 000 lb. per sq. in. = 294×10^3

E' = Modulus of elasticity of plate iron = 30 000 000 lb. per sq. in. = 3×10^7

t = Thickness of pipe plate in inches

g = Acceleration due to gravity = 32.2

R = Internal radius of pipe in inches.

Take, for example, a pipe of 5 ft. diameter, the thickness of the pipe wall being 0.25 in., and the velocity of the water in the pipe being 6 ft. per second. Substituting the above values of ω, t and R,

$$p = 6\left(\sqrt{\frac{0.434 \times 294 \times 10^3 \times 3 \times 10^7 \times 0.25}{32.2\,(0.25 \times 3 \times 10^7 + 2 \times 30 \times 294 \times 10^3)}}\right)$$

whence $p = 6 \times \sqrt{1182} = 206$ lb. per sq. inch — a pressure which approaches the rupturing point of the pipe.

As may be seen, the pressure produced by ***instantaneous*** closure is independent of the length of the pipe. An appreciable time, however, is required to close any valve, and with the introduction of the time element, the length of the pipe also enters as a factor into the problem. The theory, in general, of the phenomena which take place on instantaneous gate closure, is that the kinetic energy of the moving mass of water changes to potential energy, distending the pipe and com-

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* Church's "Hydraulic Motors," p. 208.

pressing the water. This compression of the water continues for only an instant, as immediately after compression it begins to extend itself; this act of extension again sets up the pressure and causes compression. The cycle is repeated and this continues until the friction of the water in the pipe and the molecules against each other decrease the amplitude to nearly zero. The whole occurrence is an oscillatory one and resembles somewhat the phenomenon of " surging " in electrical transmission lines carrying alternating currents. The velocity of the " wave propagation " is the same as the velocity of sound in water, and this velocity varies with varying conditions of thickness of pipe shell, modulus of material of shell, and its internal radius. The formula for the velocity of wave propagation is,

$$v = \sqrt{\frac{g}{\omega} \times \frac{E\,E'\,t}{t\,E' + 2\,R\,E}} \qquad (5)*$$

Formula (4) may also be written:

$$p = \frac{c\,v\,W}{g} \qquad (6)$$

in which v = velocity of wave propagation in feet per second.
W = weight of cubic feet of water.

$$v = \frac{p\,g}{c\,W}$$

If p = 206 as given in the foregoing problem

$$v = \frac{206 \times 144^{\dagger} \times 32.2}{6 \times 62.5} = 2\,540 \text{ ft. per sec.}$$

Assume the pipe 1 000 ft. in length. Then the time required for the wave to travel from the gate back to the end of the pipe and return to the gate is $\frac{2 \times 1\,000}{2\,540} = 0.788$ seconds. This may be termed the "time-constant" of the pipe for the velocity of water flow of 6 ft. per sec., and designated by T_c. If the gate

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* Church's "Hydraulic Motors," p. 208.

†Constant 144 is to reduce the cross-section of a cubic foot of water to square inches.

be closed within the time of one complete wave cycle, *i.e.*, 0.788 second for this case, ***the pressure set up is the same as if the gate had been closed instantaneously.***

If the pipe were 3 000 ft. long the time constant would obviously be three times the above or 2.364, say 2⅓ seconds, and in order to avoid the heavy pressure computed, the gate must not close within this time of 2⅓ seconds.

If a longer time be taken to close the gates, the pressure set up will be directly proportional to pressure due to instantaneous closing in the inverse ratio of T_c to T_x, where T_x is the time in which the gate is closed. That is $p:p'':\,:T_c:T_x$. Thus if 4.5 seconds are taken to close the gate, for conditions as above and a length of pipe of 1 000 ft., the pressure produced will be $206\times\frac{0.788}{4.5} = 36$ lb. For a 3 000 ft. length of pipe the pressure will be $206\times\frac{2.264}{4.50} = 108$ lb.

These formulæ and facts have all been experimentally proved by Joukovsky in a series of experiments conducted at Moscow, Russia, in 1897–1898, in pipes up to 24 in. in diameter. They show conclusively the necessity for compensating for the change in energy in the water column at the time of governing, if the gates are to be moved quickly for rapidly fluctuating loads. The art up to the present has not provided for this compensation except in a half-way manner, by means of relief valves.

The new method of regulating water-wheels subjected to fluctuating loads which change suddenly, is based primarily on changing rapidly the main gate-opening of the turbine without changing either the pressure in the penstock or the velocity of the flow of water through the gate-opening, at the instant of change in the gate-opening. The velocity of the water in the penstock changes slowly after the gate has moved to some new position required by change of load, and changes so slowly that there is never any substantial change in penstock, pressure, nor in the velocity of the water through the gate.

Another feature is to make the control sensitive, and removed from the jar and vibration of the gate-moving mechanism, also the prevention of "overrunning" or "underrunning." The former causes an oscillatory movement of the gate to bring it to its proper position, while the second causes "hitching" or a step-by-step movement of the gate.

Fig. 1 shows the compensating valve as applied to the penstock, by means of which the pressure in the penstock is maintained constant. The compensating device is a simple butterfly valve, working in a by-pass pipe which is tapped into the flume or penstock of the turbine. As may be seen, all water by-passed through the valve and auxiliary pipe goes around the turbine and does no work.

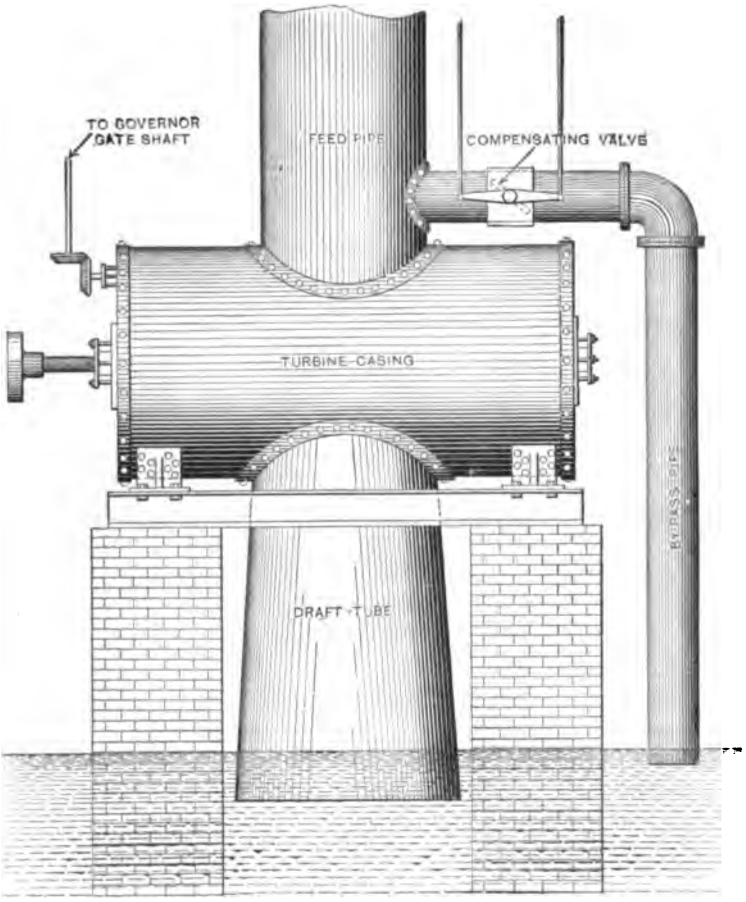


Fig. 1.

In plants where the amount of water available is in excess of that passed through the turbines, the compensating valve is kept just half-way open and a continual flow through it results. If the load on the turbine be increased, and the turbine-gate suddenly opened, the compensating valve will close at the same rate of speed as the turbine-gate opens. This turns an increased amount of water into the turbine without necessitating any change in the velocity of the column of water in the feed-pipe. Hence the speed regulation may be instantly effected. After the turbine-gate has found its new position and regulation is completed, the compensating valve returns, slowly, to its normal position of half-way open, the velocity of the column of water in the feed-pipe changing also slowly, to furnish the increased supply.

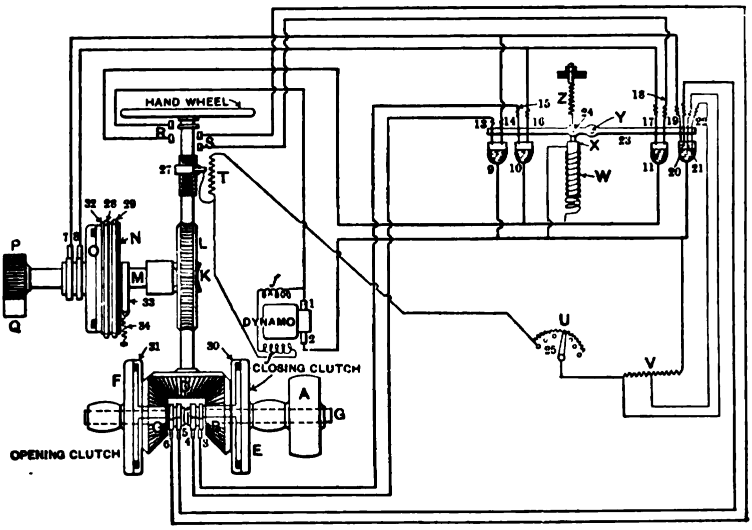
If the load on the turbine should decrease, and the gate be suddenly closed, the compensating valve will open, the movement taking place inversely to the movement of the main gate. The outlet for the water from the feed-pipe being increased, a less amount will pass to the water-wheel, and therefore the suddenly decreased gate-opening does not mean that the velocity of the water in the feed-pipe is suddenly arrested, and great pressure set up. The velocity and pressure remain practically unchanged. When regulation is completed for the new load, the compensating valve returns slowly to its normal position of half-open, thereby slowly retarding the velocity of the water column to correspond to the decreased supply required. In other words, the time-element, which is due to the inertia and incompressibility of water, and which is present in every governing arrangement, is transferred from the turbine to an auxiliary compensating device.

In those plants where all the available water must be converted into work and no waste can be allowed, this governor cannot give quite so accurate regulation as in plants where some water can be used for the purpose of governing. In this case the compensating valve is normally fully closed. If the turbine-gate be quickly closed, the compensating valve will as quickly open, thus acting as a positively operated relief valve. As soon as regulation is completed, the valve slowly shuts tight, thus limiting the water-waste to ordinary relief-valve losses.

Fig. 2 shows the various parts and connections of the governor in diagrammatic form. *G* is a shaft driven from the turbine to be controlled; its direction of rotation is immaterial. Keyed on it are the iron plates *E* and *F* which rotate with the shaft. The plates 30 and 31, which are also on the shaft *C*, and close against *E* and *F* respectively, are loose and normally do not turn. In each of these plates, 30 and 31, is a circular groove into which a coil of wire is wound. When electric current is passed through either coil, the plate in which it is laid becomes strongly magnetized.

The plates 30 and 31 are fastened to mitre-gears *B* and *C* respectively, which are loose on the shaft. Obviously, if either electric clutch is energized, the mitre-gear connected to the clutch-plate will turn with the shaft.

Meshing with the mitre gears *B* and *C* is a third gear *D*, which is keyed on to shaft *H*, running at right angles to shaft *G*. If clutch-plate 30 is energized, shaft *H* will be caused to rotate in one direction by the gear *B*; while if clutch-plate 31 be energized, the shaft *H* will be made to rotate in an opposite direction by gear *C*.



[Fig. 2.

On shaft *H* is mounted a worm *K*, which meshes with a worm-wheel *L*, the latter being mounted on a third shaft *M* which is parallel to shaft *G*. This shaft *M* is the gate-shaft, and any movement of it will cause opening or closing of the water wheel gate. The worm and worm-wheel serve both to give a low speed to the gate-shaft and to lock it in any position.

It is clear, then, that the gate will be opened or closed acording to whether *B* or *C* is energized. On shaft *M* is a third magnetic clutch, consisting of the plates *N* and *O*. Attached to *N* is a sheave-wheel 32 having two grooves in it in which lie the wire ropes 28 and 29. These ropes are attached to the compensating valve before described.

Firmly fastened on the hub of *N* is a heavy leather strap 33 which at the lower part of the loop it makes, is attached to the coil spring 34. When the clutch *N O* is energized, *N* will be caused to rotate in one direction or the other according to the direction of motion of the gate-shaft, and the ropes 28, 29, will move the compensating valve in one direction or the other at the same time that the gates are moved.

Obviously, if this sheave turns in either direction, the spring will be extended, and as soon as the clutch is released the sheave-wheel will be drawn back by the spring to its normal position. The motion of the sheave and clutch is limited to about 80 degrees.

The small dynamo is driven from the shaft, and therefore varies its speed with that of the water-wheel. It is a shunt-wound machine having laminated fields, and the magnetic density is low. Since an increase in speed will cause an increase in voltage due to the higher velocity, and this increased voltage will strengthen the magnetic field which in turn will cause an additional increase in voltage, the voltage will vary as the square of the speed.

The controller consists of a plain solenoid, *W*, which is connected with the dynamo, having inside it an iron core, *x*. This core is attached to a movable lever 23 which has mounted on it various contact-points. These contacts dip into the mercury cups below them whenever the lever is moved from the neutral horizontal position. When current passes through the solenoid it tends to draw down the core, and it is a well-known law of solenoids acting on unsaturated moving cores that the pull varies as the square of the impressed voltage. Since the voltage varies as the square of the speed, it is evident that the pull on the solenoid will vary with the fourth power of the speed.

When the speed is normal and the forces balance, the lever is in a horizontal position, and none of the contacts touch the mercury in the cups except point 22, which is longer than the others.

Following the connections, it is clear that if the core is pulled down by increase of voltage, contacts 13 and 15 will connect the dynamo circuit with clutch 30, which will cause the gate-shaft to move in a direction to close the gate. At the same

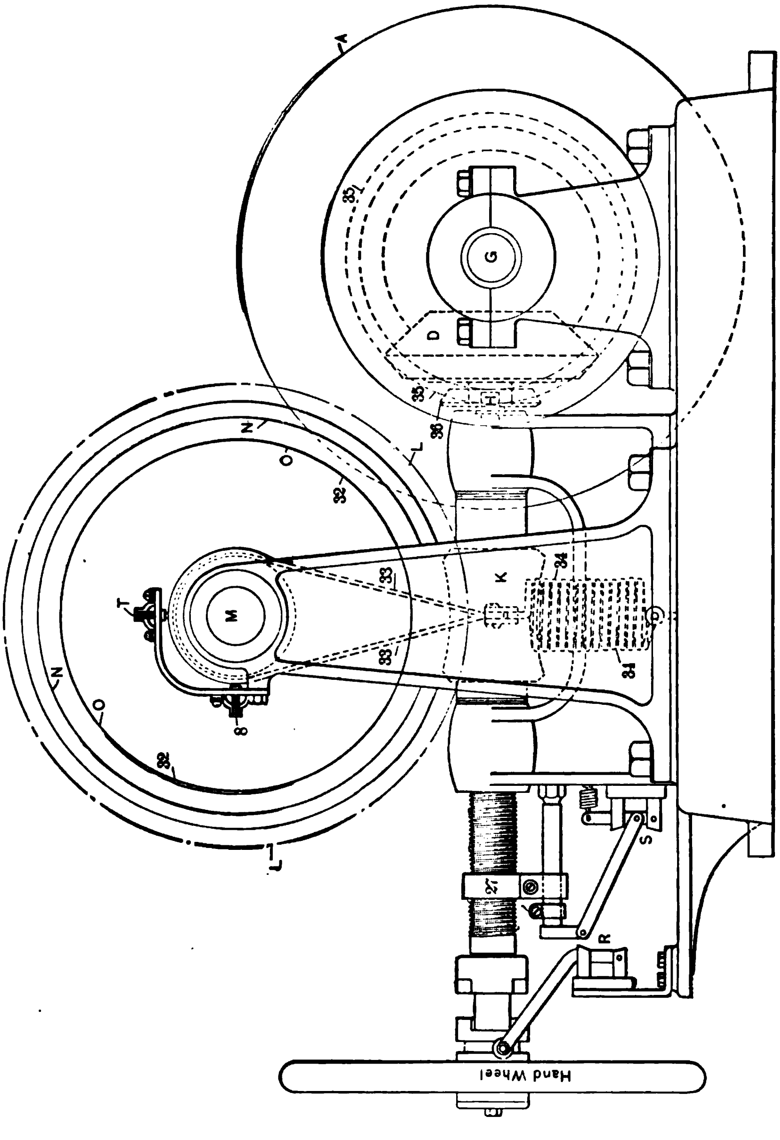


Fig. 3.

time clutch *O* will be connected to the dynamo circuit by contacts 14 and 16, and the sheave-wheel will also turn with the gate-shaft.

If the core should rise, due to decrease in voltage, the gate-opening clutch will be energized by contacts 18 and 20, while the sheave-wheel *N* will turn in a direction opposite to that in which it rotates when the gate closes, its clutch now being energized by the contacts 17 and 19. Thus the compensating valve is always moved in its proper direction whenever the main gate is moved.

When governing is completed and the speed becomes normal, the lever 23 takes a horizontal position opening the clutch circuits, and the compensator sheave, *N*, is drawn by the spring 34 back to its normal position. The water flowing through and surrounding the valve gives a dash-pot action and makes this return movement take place slowly.

The prevention of overrunning is accomplished by means of contacts 21 and 22 and the resistance *V*. Since the change in dynamo voltage causes opening or closing of the gates, it is essential that this voltage be brought back to normal before the speed has come back to its proper value. Otherwise the contacts will be held in too long, and the gate will overtravel, going past the proper position required by the load change.

By following the connections of the dynamo field circuit, it will be seen that resistance *V* is in series with the field. Contact 22, which is longer than the other contacts, is connected to the middle point of *V*, and as it touches the mercury in cup 12, when the lever is in its horizontal position, one-half the resistance is normally short circuited, the other half being included in the field circuit. If the dynamo voltage should rise, due to speed increase, the solenoid will cause the lever to move closing contacts 13, 14, 15, and 16, and opening contact 22. This movement, while energizing the proper clutches, puts the whole of resistance *V* in series with the field circuit, causing a voltage reduction before the speed is reduced. This diminished dynamo voltage allows the controller lever to return to its normal horizontal position before the speed has been brought to its proper value.

Conversely, if the speed of the turbine should fall, reducing the dynamo voltage, the spring will overpower the solenoid, and the controller lever will close contacts 17, 18, 19, 20, and 21, and carry 22 deeper into the cup. The first four will close the proper clutches; 22 being already in contact with the mercury will have no effect; 21, however, is so connected to *V* that the resistance will now be entirely short circuited and the voltage of the dynamo will rise to normal before the speed has quite reached its normal value, due to this reduction of resistance in the field circuit. These resistances can be so accurately adjusted that the gate may be caused to move exactly to its proper position without overtravel or hitching.

On an extension of shaft *H* is a threaded sleeve on which travels a nut, 27, moving in or out according as the shaft turns to open or close the gate. Obviously there is a definite position of this nut for any given gate-opening. As shown, it moves a contact-finger on a resistance *T* which resistance is also in series with the field circuit. This contact-finger and the resistance can be so adjusted that any desired amount of resistance may be cut out when the nut is in its extreme position corresponding to full gate on the water-wheels. This means that a reduced speed of the dynamo is necessary to give its proper voltage, and consequently the speed of the water-wheel is less at full load than at no load and by a definite percentage. The speed rises slightly as the position of no load is approached, the field resistance being gradually increased by the changing position of the moving finger. This speed-drop on increase of load is essential for satisfactory running of dynamos in parallel. By removing the finger the speed will be maintained rigorously constant for all loads; or by reversing the resistance connections the speed may be actually made to rise with increase of load by any desired percentage. The nut 27 also serves to open a limit-switch *S*, which is in series with the circuit leading to the clutch which opens the water-gate. If the gate be fully opened and there should be a tendency to open it still further, the nut, 27, will, by its movement, open the limit-switch *s* and thus prevent any current from reaching the opening clutch. *S*, being a spring-closing switch, it again closes the clutch circuit when the gate moves away from its extreme open position, and the operation of the governor is not interrupted.

On the outer end of shaft *H* is the starting hand-wheel which is loose on the shaft, being clutched in for starting by shoving it forward about an inch so that the clutch-jaws mesh as shown. If it were fastened to the shaft, when the governor is regulating, its fly-wheel effect would be detrimental to good speed control.

Working with the hand-wheel is the switch *R* which is in the main dynamo circuit. Shoving the hand-wheel forward and clutching it with the shaft, moves the switch blade, opening the switch. The governor cannot regulate until this switch is closed by drawing back the wheel and releasing it from the shaft. It is therefore impossible for the governor to be started and the hand-wheel be left clutched to the shaft.

The rheostat *U* is, in common with the other resistances described, in series with the dynamo field. This may be located in any convenient place, such as on the switchboard in an electric plant, and by merely turning the handle and varying the amount of resistance in circuit the speed of the turbine may be varied at will. This neither disturbs nor alters any adjustments. The normal speed of the water-wheel is as set by the operator at this rheostat. Since the gate movement takes place quickly with this governor, these machines must be made very heavy and powerful.

DISCUSSION ON "A NEW METHOD OF TURBINE CONTROL," AT PHILADELPHIA, APRIL 9, 1906.

Paul Spencer: What percentage of water will it generally require to flow through the by-pass valve in the operation, under one-half open valve, as described?

Lamar Lyndon: That is a variable, and fixed by the particular conditions under which any wheel may work. The amount of water which is passed continuously through the by-pass valve should be, theoretically, equal to the difference in the amounts of water which pass through the turbine-gate in a change from one degree of gate-opening to another. This may be better expressed by an example; where the average load changes are, say, 10% of full load, then 10% of the water, or as nearly that amount as can be spared, should go through the by-pass valve. Of course there would be times when a greater change of load than this would occur, and the by-pass could not completely compensate for this gate movement. It takes time, however, to effect any considerable gate movement, and that portion of the time during which the main gate is being moved through 10% of its travel, and over which range the by-pass does compensate, the water has become partly accelerated, and the velocity of the water has begun to change. The pressures set up, therefore, by changes in gate-opening are never very great, even if the percentage of gate change be greater than the percentage of the water passed through the compensating valve. Generally, on widely-fluctuating loads, where they jump from 50 to 80 per cent. gate, about 10 to 15 per cent. of the total water should go through the by-pass, if it can be spared; if it cannot be spared, the best that can be done will have to be done, that is all. The greater the amount by-passed the better the regulation will be.

Carl Hering: Perhaps an air-chamber at the bottom of the pipe, containing quite a lot of air, would relieve the valve from most of the shock, and would not require any continual loss of water.

Lamar Lyndon: An air-chamber helps to some extent, but only because air is elastic; it compresses or expands with changes in gate-opening, and these changes in volume can only be caused by a change in pressure in the flume. If there is no change in pressure, the air will maintain its volume constant. Of course there is not so much shock on sudden gate-closing where an air-cushion is provided, but there is a definite change in the flume-pressure. Now the effect of the pressure-change is that if the load goes off and it is desired to reduce the water-wheel speed, and the gate be quickly closed, the increased pressure will send an amount of water through the reduced gate-opening, which while it is not so great as the amount which went through the original opening, passes through at a higher velocity. In other words, the kinetic energy in the water is manifesting itself at the nozzle or gate, and the wheel instead of slowing down will actually speed up for a short time. This is found to be true of air-chambers. Whether or not an air-chamber of sufficient size has been tried, I do not know. Furthermore, an air-chamber has to be supplied by an air-pump continuously, as there are none of them that will not fill up with water in course of time by leakage or otherwise. The main point, however, is that the flume pressure *does change* with change in gate-opening, otherwise the air would not cushion; if there were not something to compress it, it would not change its volume.

Carl Hering: Yes; but the cushioning of the air, I should think, would prevent to a great extent that increase of velocity that you speak of. When the energy has spent itself on the air, it will not do so on the turbine.

Lamar Lyndon: It resolves itself into a question of velocity through the gate, which is proportional to the pressure in the flume. If the air is compressed and its volume changed, an increase of flume pressure is necessary to do this, and that means a corresponding increase in the velocity through the gate.

Carl Hering: But does not that take some time, and by that time the gate will be closed?

Lamar Lyndon: I do not know about the time-rate in compressing air, but imagine it is very rapid. At any rate, in governing changes in pressure with change in gate-opening occur even with air-chambers.

Carl Hering: Even if the compressed air chamber is large enough?

Lamar Lyndon: That I do not know. I think air-chambers would help considerably, but they will not do all that is required by the conditions of to-day.

A paper presented at the 206th Meeting of the American Institute of Electrical Engineers, New York, April 27, 1906.

STANDARDIZING RUBBER-COVERED WIRES AND CABLES.

BY JOHN LANGAN.

The effect of the tendency toward high electrical pressures is nowhere more severely felt than in the requirement for insulated wires and cables, for insulation practically controls this feature of electrical distribution. Electrical pressures can, to be sure, be increased to almost any extent, and electrical energy be transmitted to almost any distance; but to control its pathway, to regulate its course, to prevent waste, and maintain safety, this is the problem—the big underlying problem—of all electrical distributions of to-day. Five hundred volts and under are easily controlled; but pressures of 5 000, 10 000, or 20 000 volts introduce new problems, problems that were not even thought of in the days when 110 volts were considered standard practice.

On the distributing and not the generating medium, then, depends the success of the present tendency in electrical distribution. A badly insulated wire or cable will imperil the success of any system. Not only must the insulation itself be perfect, it must also be properly tested, properly installed, and properly protected. And curiously enough, engineers while examining carefully every other feature of a transmission system, will often pass lightly over the question of cables. Cables, some appear to think, are all alike. If they possess the common identity of copper, this establishes a relationship of equality, and laboring under this very general illusion, rubber-covered cables are called for and purchased with no other restriction as to quality than that they shall conform to the National Code or the Board of Fire Underwriters' rules. All this wire made subject to "code" rules passes under the general, but misleading name of " rubber covered," when, as a matter of fact, there is not an ounce of rubber in its composition. It is composed of cheap ingredients, rubber substitutes and the like, and bears about the same relation to fine rubber that a burnt cinder does to a lump of coal. Naturally, such insulation as this will not last long, since, having no rubber, it possesses no vitality, no dielectric strength, no capacity for work, and consequently becomes, in a short time, an easy prey to variations of temperature and climatic conditions. The fault here lies not with the manufacturer, but with the rules; for the rules impose no provision as to quality. All they require is a certain diameter of insulation; but whether this diameter should be wholly or partly composed of mud or rubber, they are altogether silent. Of course, no one doubts the good intentions of the framers of these rules. But as indicating how wide of the mark they go in fulfilling any requirement of good insulation, let me quote here what the rules say about testing the wires before installation.

> " Each foot of the completed covering must show a dielectric strength sufficient to resist for five (5) minutes the application of 3 000 volts per 1/64 of an inch thickness of insulation.

For example, they would require a conductor with 10/32-in. wall of insulation to stand a test of 60 000 volts; or a No. 14 wire which calls for 3/64-in. wall, a test of 9 000 volts. The absurdity of these tests must be evident to anyone having the slightest familiarity with the practical side of electrical engineering. From what source such data were derived is hard to tell; for there is not the slightest warrant either in theory or in practice for it. Even the highest grade of fine Para would stand no such test, much less the cheap, bituminous rubbish that enters virtually into every foot of what is termed "code wire."

The rules say that the insulation must stand 3 000 volts for every 1/64-in. wall of insulation. This requirement is, to be sure, absurd. But supposing this possible, who is to enforce it? No one, and no one does. The situation is like a body of law givers formulating an arbitrary law, but making absolutely no provision for anyone to enforce the law. In the case of the big telephone, telegraph and power companies, in or contiguous to New York; that is, contiguous to the manufacturers, this is simple enough, as they send a qualified engineer to make the necessary tests at the manufacturer's plant.

But what is the engineer or consumer to do who lives in New Orleans or San Francisco or Chicago? Clearly he cannot journey to New York to test his wire, and so is forced to accept any old thing that is called " rubber-covered " when, as a matter of fact, it might be entirely destitute of any rubber.

The object then of this paper is to point out and define means of standardizing rubber insulation. There is now no standard, no guide, nothing whatever to compel a uniformity of compound, excepting such as is obtained through a tedious and expensive chemical analysis. In doing this, however, it is not proposed to touch at all on technical and mathematical questions, such as capacity, heating, static conditions, and the like. These are matters which properly concern the electrical and consulting engineer, and while of great importance, are, after all, subordinate to the more vital and practical questions of good insulation. With this assured, everything else logically follows. And besides, theoretical formulas are of little value unless based on something specific and definite. With variable and uncertain premises, you cannot avoid variable and uncertain conclusions. And it is because of this widely varying character of rubber insulation that nearly all such formula are uncertain and misleading. Under existing conditions then the electrical engineer has little in the way of data to guide him in obtaining reliable insulation.

This, I know, sounds very heterodox. For if there is any one dogmatism to which electrical practice seems unchangeably attached, it is that of a firm belief in the value of a voltage test in determining dielectric efficiency. Yet nothing could be more misleading . Indeed it may be affirmed that a potential test is, in itself, no criterion whatever of permanent value. As an aid —as a collateral agent—it does, however, play an important part. But as indicating, much less proving, permanent merit, nothing could be more misleading and empirical. And the reason for this will, on a little reflection, be obvious enough.

You are all familiar with the influence of certain oils on high-tension switches and transformers. These withstand potentials that, without these adventitious aids, would be altogether impossible. Certain mineral and vegetable oils will, therefore, stand extremely high pressures, and in this we have a clue, and even a proof, why many obviously cheap insulating compounds stand very high potential tests, and yet will, in a short time, break down in actual service. The logic of this anomalous condition is, that when these communicated oils in the compound evaporate—as they will in a short time—the temporary and adventitious virtues they possess, disappear also, and the insulation deprived of this artificial support, quickly falls into disintegration and decay. This is the inevitable history of all such combinations. The situation is somewhat akin to a horse " doped " for a race, who shows a surprising turn of speed for a short distance, and then suddenly collapses. From this it will be seen that a puncture test is, in itself, an uncertain proof of dielectric excellence.

What is it then that constitutes good insulation, and how can we ascertain and know it? This is the all important question. With this assured, everything else logically follows. The concensus of opinion, derived alike from theoretical and practical experience, is that rubber is the best of all insulating materials. There will, it is believed, be little dissent from this established conclusion. Its use to-day is practically universal. It has survived the vicissitudes of time and experience, has successfully refuted the claims of all alleged substitutes, and stands to-day the unrivaled and indisputable factor in transmission, without which electrical progress would be uncertain and precarious. We need not, therefore, resort to any detailed proof of rubber's right to insulating preeminence. Twenty years of practical experience justifies the wisdom of its use. In fact, it is the quantity and quality of the rubber in the compound that differentiates the grade, and determines the price of every wire and cable on the market.

But while rubber is the principal feature of good insulation, it is not the only feature. As a matter of fact, rubber in itself is valueless as an insulating medium. The reason for this is that in its native condition it absorbs a certain amount of moisture, and when exposed to the air readily oxidizes. These factors of disintegration naturally preclude its use as a distinct and separate constituent for insulating purposes. But in conjunction with other ingredients, and when allied with sulphur, and properly vulcanized, it becomes not only absolutely waterproof, but indeed, under normal conditions, one might say, indestructible. From this it will be seen that there are two factors involved in good insulation. The fundamental thing is, of course, that the rubber be fine Para. But it does not matter how good the rubber is or how much of it is incorporated in the compound, if the vulcanization is not properly carried out, the insulation will be defective. In fact, it is hardly exaggerating things to say that the art, or the science, of rubber insulation, resides chiefly in the proper understanding of vulcanization. This consists in the addition of a certain percentage of sulphur—generally about 3%—to the rubber and then subjecting this association to a certain temperature for a certain duration of time. The result is vulcanized rubber. Vulcanization, then, is that more or less mysterious factor which gives the rubber longevity, durability and immunity from oxidation when exposed to atmospheric and other conditions. In short, it is what may be called "embalming" the rubber. Without it rubber is absolutely worthless for insulating purposes; with it, it becomes, under normal conditions, virtually indestructible.

Bear in mind, however, that there are many and different grades of rubber, all varying in price as in quality, and it is only by a knowledge and recognition of this wide diversity of character that an engineer can intelligently make up specifications and rigidly enforce them.

Chemically considered, rubber is differentiated by the amount of acetone soluble, extractive, or resinous matter which it contains, and physically by its tensile strength. Both, of course, are closely related; for where it is chemically poor, it is also physically weak. In brief, a high percentage of resinous matter is indicative of the cheaper grades, such as African, Madagascar, and some South American products; and a low percentage indicates the best grades of fine Para, such as Bolivia, Maderia, and Up-River. The best grades differ little as to merit, whereas the others fluctuate a great deal as to quality and price. In the former, the resinous matter is as high as 20%, and in the latter, it seldom exceeds 1%.

This, then, is the chemical reason for the high regard in which fine Para is held, and it is with this grade that the following specifications and tests will be exclusively associated. You will observe from this, that in proportion as rubber is high in extractive matter, its estimation is low; and vice versa, that as it is low in extractive matter, its price is high. In other words, both quality and price will vary inversely with the amount of resinous matter.

These commercial aspects are the result of practical experience; for it has been found that the life of rubber bears a direct relationship to the resinous matter it contains. It is, therefore, of evident importance to have an elementary knowledge of these characteristics; for it is a lack of this knowledge that is responsible for the wide and general mischief caused by the belief that all wires and cables called "rubber-covered" are alike, when, in reality, if they possess any rubber at all, they may have nothing in common but the copper conductor.

With the physical aspect of rubber, you are all, no doubt, more or less familiar. It is, as you know, astonishingly strong; indeed, it is doubtful if a piece of fresh fine Para, of a few inches in diameter, could possibly be broken by the average man. It is very elastic too, stretching to such an extent as to render a substance in itself opaque, perfectly translucent.

Now, from an analysis of these facts, it will be perfectly obvious, that, since rubber is in itself very strong and very elastic, these characteristics should be present in any insulated wire in proportion to the quantity and quality of the rubber in the insulation. And from this it would seem that good insulation resolves itself largely into a question of tensile strength. This, on the whole, is true. But owing to the immense influence exerted by vulcanization, this is subject to important modifications which will be referred to, and enlarged on, as we progress in this paper.

It is well known that while vulcanization, when properly done, does not alter the constitution of rubber, yet it can be made to affect adversely or deceptively modify its behavior. For example, if it is over-vulcanized it will become hard and somewhat brittle; and if under-vulcanized, it will become flabby and inert. In either case the result is indicative of imperfect insulation, and will not fulfil the requirements of a tensile test. In the one case it will break, and in the other it will stretch but not return. Good insulation, then, is clearly indicated by its prompt return after being stretched several times to, say, three to four times its length. Stretching to three and one-half times its length, as above indicated, is, roughly speaking, equal to about 800 lb. to the square inch. But bear in mind that merely stretching implies nothing; almost any kind of rubber will stretch. But where the first-class rubber is, the insulation will jump back with a vigor somewhat similar to a magnetic pull. What, however, is aimed at in this test, is a tensile strain of not less than 800 lb. to the sqaure inch, and wherever practicable, this is much more effective in weeding out the cheaper grades of rubber, than the elongation test alone is.

Now, it has been clearly and repeatedly proved that where there is 30% of fine Para in the insulation, this physical test is easily obtained. Of this there is not the slightest doubt. In obtaining this proof, every manufacturer on the American market unwittingly contributed to the result. It was felt that to rely on any one brand or any one make would be one-sided and inadequate, and so every grade or combination of grades of different manufacturers was chemically analyzed, in order to verify the physical tests obtained. The object was to discover a physical test that would enable the electrical engineer to obtain by a simple, inexpensive method, what can, with precision, be obtained only by a tedious and expensive chemical analysis. The original calculations were based on the assumption, that since 30% of Para does, unmistakably, produce the tensile tests already referred to, any insulation fulfiling these, must, necessarily, possess 30% also. But it was found that a combination of a lesser amount of Para and a large amount of a cheaper grade of rubber, would initially, at any rate, produce the same test that 30% of fine Para would. But to do it successfully, the compound has to contain between 40 and 50% of this cheaper grade. This can best be explained by a single example: bids were asked for on a 20 000-volt cable, the insulation to contain not less than 30% of fine Para, free from all shoddy, rubber substitutes, and the like. The first two samples submitted did not meet the physical test, and were rejected. The third experiment was successful, met all the requirements specified, electrically and physically, but on a chemical analysis, here is what it contained: 15% of Para and 30% of some cheaper grade of rubber, making all told, 45% to meet the requirements of the specifications. Now, this is an extremely interesting exhibit, the import of which will, it is hoped, be evident to all.

The first lesson that it conveys is, that this physical test, rigidly enforced, precludes absolutely the use of shoddy, bituminous products, and even the cheap grades of rubber. The second is, that it takes 40 to 50% of a cheaper combination to do what 30% of pure Para will do.

Another way of looking at it is, that the physical test does not, in itself, prove that the insulating compound contains nothing else but pure Para. This, to be sure, is a drawback to its exclusive use where the best results are wished for. But, on the other hand, if it does not give you the best, it does, at any rate, wipe out all cheap rubber substitutes, and gives you an insulation that, if not equal in durability to 30% of Para, is immeasurably superior to anything you can now obtain by any other means short of a chemical analysis. This, in itself, is an immense advantage. It enables the distant engineer to do what he could not do heretofore; to tell off-hand what the character of the insulation is; that is, to strip the insulation from the wire, and test according to the specifications herein to follow. Any one can verify the value of it by getting some code wire, and applying this test to it, or indeed, for that matter, the best wire to be found on the market, and see what the comparison will reveal.

In this test we have, it is believed, a cure for the growing degeneration of National Code wire. It enables the Board of Underwriters, architects, and engineers—all who are responsible for this class of work, to test off-hand, and without expense or trouble, the character of the insulation. .

But while it does all this, the fact remains that the physical test alone, does not compel precise results—does not necessarily compel 30% of fine Para in the insulating compound. It does, however, compel 30% of rubber. This, as I have already said, is an immense advance over the bituminous products you could ordinarily get. But there is rubber and rubber as there are men and men, and I am purposely reiterating this difference again, so that you will carefully distinguish between cheap grades and the fine Para.

How to obtain—how to compel—30% of fine Para in the insulating compound is, then, the problem, where the best and most enduring results are desired. There is, unfortunately, no way short of a chemical analysis of proving this. And even then, we are constantly beset by stubborn facts and obscure difficulties which may neutralize the value of an anlaysis unless the specifications be carefully worded. For the chemist —and he must be a very skilful one at that—can prove nothing whatever except by imposing rigid restrictions as to what the compound shall contain. For example: were you to merely say that the compound shall contain 30% of *rubber* and leave it at that, then the analysis would prove nothing more than that there was 30% of rubber it in, but whether it was good, bad or middling rubber, it could not determine. Now, this is one of the perplexities of a chemical analysis of rubber insulation. There is, however, a way of arriving at chemical precision, one which proves indubitably the character of the rubber employed.

In the earlier part of the paper, it was noted that the extractive or resinous matter in the rubber differentiated its grade; that is, the best grade of rubber has seldom more than 1%, and the cheaper, varying from 5 to 20%. From this it will be seen that by limiting the amount of resinous or extractive matter that should appear on a chemical analysis in the compound, you thereby determine the grade of the rubber. Of this, there is not the slightest doubt. You can verify this for yourself in the following way: ask for a price first on a wire or cable to contain, say 30% of rubber, and compare the cost of this with another which calls for 30% of fine Para, the extractive matter in which, on a chemical analysis, shall not exceed from 3 to 5%. To all who are keenly analytical, the question will naturally occur, why allow 3 to 5% of extractive matter in this analysis, when the fine Para itself has native to it, only about 1 to 1½%. Well, in the first place, during vulcanization, the extractive matter in a 30% fine Para compound, for some cause, increases to about 3%. We do not, at present, fully understand why this should be so, but it is so. And, in the next place, the addition of some extractive matter to this inherent or natural amount, is considered by the manufacturers a good thing for the insulation. But the total in the completed or braided wire should never exceed 5%; for beyond this limit the chemist cannot differentiate the grade of the rubber, and thus the value of the analysis is compromised and useless. For this reason, tests should be made on the completed wire, rather than on an unfinished sample.

The following specifications will, it is hoped, in view of what has been said, be intelligible to all.

SPECIFICATIONS FOR RUBBER-INSULATED WIRES AND CABLES.

All conductors to have at least 98% conductivity and to be thoroughly and evenly tinned.

The insulating compound to contain not less than 30% and not more than 32% of fine Para rubber. No shoddy, reclaimed rubber, rubber substitutes, or the like, must, in any form, be in the compound, the extractive matter of which, when chemically analyzed, must not exceed 5%.

All wires and cables properly insulated in accordance with the above provisions must, after 48 hours' immersion in water, at a temperature of 60° fahr. and before tape, braid, or lead is applied, show the following insulation resistance and voltage tests. Insulation test to be made with a battery of 100 volts after one minute's electrification.

LOW POTENTIAL, 600 VOLTS.

B. & S. Gauge.	Wall.	Voltage Test for 1 Minute.	Insulation Resistance.
No. 14 to 8	3/64 in.	1 000	1 000 megohms per mile
6 to 2	4/64 "	1 000	1 000 " " "
1 to 4/0	5/64 "	1 000	1 000 " " "
250 000 to 500 000 cir-mils.	6/64 "	1 000	750 " " "
550 000 to 1 000 000 "	7/64 "	1 000	500 " " "

MEDIUM POTENTIAL, 3 500 VOLTS.

B. & S. Gauge.	Wall.	Voltage Test for 1 Minute.	Insulation Resistance.
No. 14 to 8	3/32 in.	5 000	3 000 megohms per mile
6 to 2	3/32 "	5 000	2 500 " " "
1 to 4/0	3/32 "	5 000	2 000 " " "
250 000 to 500 000 cir-mils.	3/32 "	5 000	1 000 " " "
550 000 to 1 000 000 "	4/32 "	5 000	600 " " "

5 000 VOLTS WORKING PRESSURE.

B. & S. Gauge.	Wall.	Voltage Test. for 1 Minute.	Insulation Resistance.
No. 4 to 4/0	6/32 in.	10 000	2 500 megohms per mile
250 000 to 500 000 cir-mils.	6/32 "	10 000	1 500 " " "
550 000 to 1 000 000 "	6/32 "	10 000	1 000 " " "

11 000 VOLTS WORKING PRESSURE.

B. & S. Gauge.	Wall.	Voltage Test for 1 Minute.	Insulation Resistance.
No. 4 to 4/0	9/32 in.	15 000	4 000 megohms per mile
250 000 to 500 000 cir-mils.	9/32 "	15 000	3 000 " " "
550 000 to 1 000 000 "	9/32 "	15 000	1 500 " " "

B. & S. Gauge.	Wall.	Voltage Test for 1 Minute.	Insulation Resistance.
No. 4 to 4/0	10/32 in.	20 000	5 000 megohms per mile
250 000 to 500 000 cir-mils.	10/32 "	20 000	4 000 " " "
550 000 to 1 000 000 "	10/32 "	20 000	2 500 " " "

B. &. S Gauge.	Wall.	Voltage Test for 1 Minute.	Insulation Resistance.
No. 4 to 4/0	12/32 in.	20 000	6 000 megohms per mile
250 000 to 500 000 cir-mils.	12/32 "	20 000	5 000 " " "
550 000 to 1 000 000 "	12/32 "	20 000	3 000 " " "

For railway signaling, fire alarm, telephone, and telegraph purposes the walls of insulation should not be less than the following:

B. & S. Gauge.	Rubber Wall.	Voltage Test for 1 Minute.	Insulation Resistance Per Mile.
18	1/16 in.	1 000	3 000 Megohms
16	1/16 "	1 000	3 000 "
14	1/16 "	1 000	3 000 "
12	5/64 "	1 000	3 000 "
10	5/64 "	1 000	3 000 "
8	5/64 "	1 000	3 000 "
5	5/64 "	1 000	3 000 "
6	3/32 "	2 000	2 500 "
4	3/32 "	2 000	2 500 "
2	3/32 "	2 000	2 500 "
1	3/32 "	2 000	2 000 "
0	3/32 "	2 000	2 000 "
00	3/32 "	2 000	2 000 "
000	3/32 "	2 000	2 000 "
0000	3/32 "	2 000	2 000 "

ELONGATION TEST.

In addition to the above tests, the insulating material of every wire must stand an elongation test of stretching three times its length several times; that is, a piece 2 inches long must stretch to 6 inches and promptly return to within 20% of its original length. It must then stretch four times without break or rupture and return to 25% of its original length.

This elongation test is intended principally for Code wire, and would, even by omitting all conditions as to rubber, compel results that would be entirely reliable and satisfactory for all conditions of Code use.

TENSILE TEST.

Any piece of insulation, about ½ in. wide by $\frac{1}{16}$ in. thick, stripped from the completed wire or cable, should stand a tensile strain of 800 lb. to the square inch, and stretch to 3½ times its length without rupture.

The following provision will be found useful: the manufacturer must notify the electrical engineer when wire is ready for testing, and in no instance must shipment be made until notified of approval and acceptance as per above tests.

TESTS.

In carrying out the tests embodied in these specifications, there is sought something quite different from the ordinary potential and electrical tests. Heretofore the electrical engineer, when he imposed any test at all, relied solely upon a puncture test. If it met these requirements he asked for nothing more. If a wire or cable withstood a very high puncture test, it was looked upon as a *prima facie* evidence of dielectric excellence, forgetting that, had the pressure been maintained a moment longer, the insulation might have broken down. It is a most mischievous practice, and a wholly misleading notion of safety, to push a test up to, or even to approach closely the dielectric limit of the insulation; for it is no uncommon occurrence to find the very best insulation hopelessly injured by this practice. It may not be well known, but it is a fact, nevertheless, that it is the rise in temperature which accompanies a rise in potential, that is so destructive of rubber insulation. The layers next the copper naturally feel these injurious effects first, and they thus successively carbonize and break down with this increasing elevation of pressure and temperature.

It frequently happens that a cable may pass an exacting puncture test, and be to all appearances in first-class condition, when in reality the insulation has been so strained that it collapses at the first physical or potential strain imposed upon it. This is a frequent occurrence. A potential test is not, therefore, in itself, an exact nor even an approximate proof of insulating merit.

You must not, however, assume from this, that puncture tests are of no value, for they are, and of great value, but to be of value, they must be employed, not as a means to *destroy* merit, but to discover imperfections. Here, should be their chief object; and in this respect they are of incalculable importance to the electrical engineer.

It is obvious that a cable may be well made up of very poor material, or it may be imperfectly made up of the very best material. In the one case, there is good workmanship with poor material, and in the other, bad workmanship with good material. In the first case the cable is intrinsically poor, and in the second it is intrinsically good but imperfectly made up. This imperfection may be slight or considerable; it may be due to a piece of gravel or an air-bubble in the compound. In a case like this, nothing but a puncture test will discover the fault. But the test should be nominal, and there is no need of pushing it to the point of rupture. If there is any weakness or imperfection, 5 000, 10 000, or 15 000 volts, depending on the thickness of the wall of insulation, will discover it, after one minute's application.

It may be laid down as a safe, general rule that a puncture test should never exceed double the working pressure, but this is true only up to a certain limit, say 15 000 volts working pressure. After 25 000 to 30 000 volts are reached, the temperature increases so fast that it becomes increasingly destructive to the vitality and durability of the insulation.

Much of the present tendency for high potential and breakdown tests, is the result of an altogether erroneous comparison with tests imposed on paper-insulated and similar cables, which must, of course, be lead-covered, before any test can be made. Such tests are of necessity " dry tests," whereas rubber-covered cables, on the contrary, are soaked in water and tested before the tape, braid, or lead is applied. For this reason it is hardly an exaggeration to say that double the potential imposed on a paper cable, is no more exacting than half the amount applied to a rubber cable. To expect, then, on a rubber cable anything like the same strain that is ordinarily put on a paper cable, would be, in effect, expecting rubber to stand double what paper stands.

In saying this, there is no intention whatever, to institute comparisons between rubber and paper, or detract in any way from the merited recognition accorded to paper for certain work. All that is intended is merely to point out the fallacy of comparing tests, that, in their very nature, admit of no comparison.

The specifications and tests here incorporated will, it is hoped, obviate this well-meaning but destructive practice. The really vital point is to make sure of the rubber in the insulation, and this being assured by the tests referred to, all that is needed in the way of a potential test is enough to disclose imperfections arising during the process of manufacture.

The virtue of an insulation test is, as yet, imperfectly recognized by the electrical profession. In fact, engineers in general altogether underestimate the value of a high insulation resistance. It will doubtless surprise many to hear that as a criterion of merit, it is immeasurably better than a voltage test. The probable explanation of this seeming paradox is, that while a cheap compound will stand initially a high potential test, the current, because of this cheapness, will sneak through it, and show a low insulation resistance.

Conversely, then, a high insulation resistance is indicative, of a high-grade compound. At any rate, this much is certain, that in insulating compounds having 30% fine Para, there is always associated with them, a very high insulation resistance; whereas in cheap compounds, the reverse is equally evident. In Code wire, for example, one cannot get over 400 or 500 megohms per mile, while the best grade of rubber will show three or four times this amount. A high insulation test should, therefore, wherever possible, always supplement a physical test, as it tends to elevate the grade of the compound. When, however, a chemical analysis is contemplated, the necessity for this is not so obvious; but where it is not, the two, if associated, will produce the most satisfactory results.

The reason for limiting the rubber in the compound so as not to exceed 32% is this: it was found that by incorporating a large amount of cheap rubber with a small amount of Para the physical test could be nominally complied with, thus defeating the intention of the specification to obtain the best insulation. The object of this limitation, then, is that by not permitting fine Para, or any other rubber, in excess of this amount, the best rubber has to be employed to meet the requirements of the physical test.

Obviously, one manufacturer cannot afford to use 35 to 40% of fine Para at a materially less price than another who uses only 30%; and where an analysis reveals such large amounts, or anything in excess of this limitation, there can be no doubt whatever, as to the inferior grade of rubber used. This provision, then, is extremely important, because with its compulsory observance there would be little need of a chemical analysis at all, except in the event of a dispute, when it could be resorted to as a final court of appeal. The tensile test is, under the limits referred to, sufficiently reliable and adequate for every purpose, for in it, we have a means of standardizing rubber insulation that can neither be evaded nor denied.

A paper presented at the 206th Meeting of the American Institute of Electrical Engineers. New York, April 27, 1906.

COMMENTS ON PRESENT UNDERGROUND CABLE PRACTICE.

BY WALLACE S. CLARK.

There are certain practices now so general in underground cable work for light and power in America as to be almost standard. Some of these practices may be examined with advantage.

Cable making was an established art at least a quarter of a century before cables were made for service beyond signal transmission. Its development, therefore, has been somewhat more gradual than the development of the apparatus for generating the energy transmitted. Perhaps this greater age has tended to undue conservatism.

Practically all cables of the class under consideration have continuous metallic sheaths. Is this the best engineering?

LOW-TENSION CABLES.

These are run in conduits with some portion of the circuit grounded. In railway practice one leg of a two-wire circuit, and in lighting the neutral wire, is permanently earthed. The continuous sheath on these cables is an invitation to stray currents and consequent electrolysis. While dry, well-vitrified tile is a fair insulator, but in time the joints between the sections provide leakage spots. Further, many ducts are damp at certain seasons if not during the entire year, making the dirt which accumulates a sufficiently good conductor to offer an additional path for stray currents.

Grounding the sheath at each manhole was announced as a cure for electrolysis, but instead of a cure it has been found in some cases to be a cause of trouble. The amount of current carried by the sheath is greatly increased, producing a drop in electromotive force between ground strips sufficient to cause a flow of current to earth at some intermediate point in the duct and in sufficient volume to give trouble.

In case of a burn-out, the continuity of the sheath aggravates the trouble. Whether the initial fault is in the duct or in a manhole, the tendency of the arc is to travel along the cable, and without a sufficient volume of current to operate safety devices, if such are in the circuit. If at any point another continuous metallic sheath comes within reach of the travelling arc, the fine earth it offers insures two cables out of service. Almost every large installation can furnish from its history a serious and expensive experience, illustrating this point. Further, during the burn-out a heavy current flows in the sheath and this may leave the sheath by arcing to earth on some perfectly good section of cable, melting a hole in the lead.

The volume of current carried by these low-tension conductors in regular practice is so large that in many cases circuit-breakers or fuses will not operate with the current due to the short circuit. The ammeters are a poor guide, especially in railway work. In many cases, the outside end of the line is solidly connected to a network which is capable of furnishing all the energy needed to maintain the arc after the defective cable is disconnected at the station end; so we cannot depend on protective apparatus as used to-day for prevention of these troubles.

Omitting the sheath will cure all the above ills. To do this would bar paper, leaded jacketed cables absolutely, and would increase the depreciation account if some type of cable insulation needing lead only, as wood needs paint, were used. Abandoning the lead entirely is an economic possibility with only very large conductors, where it may be cheaper to renew the insulation on a non-leaded cable, say once in 10 years, than to renew a lead-jacket cable once in 20 years. These figures are, of course, merely used for comparison, for there is little accurate knowledge as to the life of insulated cables. If, therefore, we are compelled to use a lead sheath, the writer believes that it should be interrupted by some form of insulating joint on low-tension cables.

If this plan is carried out, a serious difficulty is the inability to test the insulation of the cable. This may be met by the use of an insulated wire—proof or pressure wire—in the outer layer of strands forming the copper core. Such a wire should be insulated with some material like treated paper, susceptible to the absorption of moisture.

For the purposes of initial tests when the cable is installed, the joints in the sheath may be bridged by fine fuse wires, which are afterwards removed. Several methods of utilizing the pressure wire are suggested below:

(a) The outer end of the pressure wire is insulated, in which case periodic tests of this wire for insulation resistance will show any incipient fault in the main conductor. Between tests the wire can be connected to a drop annunciator or other signaling device which will become operative in case of a burn-out, since the pressure wire will become " alive " before any great amount of energy flows through the fault. It might also be made to operate a current-interrupting device.

(b) The wire may be used to read the pressure at the far end of the line. The potential of the wire should be opposite to that of the conductor in which it is embedded. A burn-out would either make the wire "dead " or of the same potential and sign as the main conductor.

This change in potential could operate devices as above outlined under heading (a). If used in this way, the pressure wire would have to be disconnected at the far end for insulation tests; a much easier operation, however, than the disconnecting and insulating of the main conductor, and one not interfering with working the line.

A secondary use of the pressure wire would be to calculate the temperature of the main conductor by measuring variation in the resistance, figuring from length, loss in line, and known resistance cold.

HIGH-TENSION CABLES.

With high-tension lines some of the troubles due to the metallic sheath on low-tension cables are less marked. The load is usually more uniform and subject to less violent fluctuation, especially where sub-stations with batteries are in use, allowing protective devices to be set so as to operate more promptly.

Further, in the case of a network such cables are usually protected against a reversal of current, so that the arc at the fault is not maintained by energy derived from the network or sub-station.

The metal sheath on high-tension cables must be earthed to prevent danger to life, and also risk of puncturing the insulation by cumulative static charge. It is probably unnecessary to use insulating joints in the sheath of high-tension cables, except in some special case where local conditions require them to prevent an excessive amount of stray current being carried.

For a number of years the writer has been advocating multiple-conductor cables for arc circuits instead of several cables in the same duct in trunk lines. The running of a lot of small cables in one duct is not good practice; a burn-out on one cable is likely to injure others in the duct, and the withdrawal of a defective cable for repairs is apt mechanically to injure the other cables.

A properly designed multiple-conductor cable costs less, is easier to install, and safer to operate. Of course, one conductor in a duct is ideal, but barred by cost in small sizes.

INSULATION.

Should we use a heavy wall of a cheap so-called rubber compound or a lighter wall of better quality? Examination of engineers' specifications shows some curious ideas prevalent. Thick insulation has, among other points, these against it:

1. Increased size of cable, involving increased cost of the sheath, duct space, and handling.
2. Thicker wall for heat generated in conductor to flow through (partly balanced by increased radiating surface) resulting in higher operating temperature in the copper core.
3. Most serious of all, however, is the frequent acceptance of a poor quality of compound having a very short life.

The last sentence contains a clue to the evil repute in which many engineers hold rubber-insulated conductors. There appears to be some confusion in the minds of engineers as to certain basic facts concerning what is generally called rubber insulation. High-insulation resistance, high-puncturing resistance, and durability do not of necessity bear any relation to one another. An insulating material may have any one, or any two of these, and be deficient as to the remaining quality or qualities. High puncture resistance is the least difficult; high insulation resistance somewhat more difficult; and durability the most difficult of attainment. A reasonable amount of good rubber in the present state of the art, as known to the writer, is necessary to insure durability.

The table of puncturing voltage, insulation resistance, and electrostatic capacity tests given herewith shows that these factors are not very good guides as to the durability of the insulation.

Relative Amount of Rubber.	Breakdown Electromotive Force.	Insulation Resistance Megohms Per Mile.	Capacity Microfarads Per Mile.	Relative Deterioration in one year in Elastic Limit.
1	17 000 volts	534	2.	66%
2	19 000 "	1 185	1.2	30%
3	18 000 "	1 150	1.	20%

The above figures are based on 12 tests of each class; they are quoted, not to show absolute values but to make clear the point that the cheaper grades of insulation do not retain their elasticity. It should be noted that rubber compounds change quite rapidly at first and that the rate of deterioration becomes less with time.

As an appendix to this paper, there is a set of specifications adopted by the Rubber-Covered Wire Engineers' Association after more than a year's work. These specifications are better than any heretofore seen by the writer.

An idea of the life of a rubber cable leaded and operating at 11 000 volts, 25 cycles, is presented below through the kindness of Mr. H. Alverson, Superintendent of the Cataract Power & Conduit Company, Buffalo.

	Cable No. 2	Cable No. 3
In service Nov. 23, 1897	21 493 ft.	21 493 ft.
Added Jan. 22, 1899	10 559 "	10 559 "
Total in service from Jan. 22, 1899	32 052 "	32 052 "

BURN-OUTS.

Dec. 28, 1897, Cable No. 2, 20 ft., from end of pole line; cause, no end-bells.

May 11, 1898, Cable No. 3, same as No. 2.

May 2, 1899, Cable No. 3, 8 931 ft., from end; cause, not ascertained.

Oct. 12, 1899, Cable No. 3, 14 845 ft., end in joint.

1900, none.

1901, none.

May 17, 1902, Cable No. 2, 14 224 ft., from end in cable vault; mechanical injury.

1903, none.

Sept. 19, 1904, Cable No. 2, 14 204 ft., from end; laborer drove gas pipe into conduit and cable.

1905, none.

March 27, 1906, none to date.

In May 1900, Cable No. 2 was tested with 22 000 volts for 24 hours.

Size of cable, 3/0; conductors, three; insulation on each conductor 9/32-in. thick; no over-all jacket.

The most noticeable fact brought out is that although most of the cable is more than eight years old, there is no indication of any electrochemical or other electrical action weakening the ability of the insulation to withstand the working pressure.

Further, these cables originally operating alone are now in multiple with some 32 miles of three-conductor cables, and therefore subjected in all probability to more severe strains due to surges than when first installed. These are, I believe, the oldest working rubber-insulated, 11 000-volt, three-phase cables in use to-day.

These data on rubber insulation are important, if, as the writer believes, cables for very high tension will be made with combined insulations of varying capacities, rather than with a homogeneous insulation of any insulating material now in use.

There is one more point which should be touched on, if only to repeat and emphasize what has already been said by Mr. Fisher*; that is, the lack of judgment used by engineers in specifying the thickness of the lead sheath.

Cables are, roughly, of two classes: those whose insulating material is not injured by submersion in reasonably clean water, and a second class which will not withstand such test. For cables of the first class the metallic sheath is primarily for the purpose of lessening the rate of deterioration, and secondarily to protect against mechanical injury during installation. The sheath on these cables should be comparatively thin and be proportioned to the weight of the cable. The second class of insulation will only be serviceable so long as the sheath is intact, and therefore the metal should be heavier and show less variation as to its thickness with the weight of the cable.

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*TRANSACTIONS, A. I. E. E., 1905, Vol. xxiv., pp. 397-414.

The above does not mean an endorsement of the specifications which call for ⅛-in. lead on No. 6 and also on 2 000 000 cir. mils, but rather the suggestion of a minimum thickness of $\frac{3}{32}$-in. on paper- and jute-insulated cables, increasing gradually in proportion to weight and diameter to, say, $\frac{5}{32}$-in. on the largest cables (2 ⅞ in.) now in common commercial use.

In closing, I hope that the INSTITUTE will take up actively the standardization of some of the principal dimensions of underground cables.

APPENDIX.

SPECIFICATIONS 30% RUBBER INSULATING COMPOUND.

RUBBER-COVERED WIRE ENGINEERS' ASSOCIATION.

The compound shall contain not less than 30% by weight of fine dry Para rubber which has not previously been used in rubber compounds. The composition of the remaining 70% shall be left to the discretion of the manufacturer.

CHEMICAL.

The vulcanized rubber compound shall contain not more than 6% by weight of acetone extract. For this determination, the acetone extraction shall be carried on for five hours in a Soxhlet extractor, as improved by Dr. C. O. Weber.

MECHANICAL.

The rubber insulation shall be homogeneous in character, shall be placed concentrically about the conductor, and shall have a tensile strength of not less than 800 pounds per square inch.

A sample of vulcanized rubber compound, not less than 4 inches in length, shall be cut from the wire with a sharp knife held tangent to the copper. Marks shall be placed on the sample 2 inches apart. The sample shall be stretched until the marks are 6 inches apart and then immediately released; one minute after such release, the marks shall not be over 2⅜-in. apart. The sample shall then be stretched until the marks are 9 inches apart before breaking.

For the purpose of these tests, care must be used in cutting to obtain a proper sample, and the manufacturer shall not be responsible for results obtained from samples imperfectly cut.

ELECTRICAL.

Each and every length of conductor shall comply with the requirements given in the following table. The tests shall be

30% Rubber Compound. Megohms Per Mile. 60 Deg. fahr. One Minute Electrification.
Thickness of Insulation.

	3/64	2/32	5/64	3/32	7/64	4/32	5/32	6/32	7/32
1 000 000 cir. mils					200	210	235	265	300
900 000 "					235	250	280	315	360
800 000 "					270	290	325	370	420
700 000 "					305	325	370	420	480
600 000 "					340	365	420	470	540
500 000 "				350	375	405	465	525	600
400 000 "				390	420	450	530	600	670
300 000 "				430	470	505	590	680	750
250 000 "				455	500	540	630	720	810
4/0 stranded			440	480	520	565	660	750	840
3/0 "			450	490	535	580	675	770	860
2/0 "			460	500	545	590	690	790	880
1/0 "			490	540	590	650	760	860	950
1 solid			520	580	635	700	830	950	1 060
2 "		500	550	615	680	750	900	1 040	1 160
3 "		530	585	650	715	795	940	1 080	1 210
4 "		560	620	690	750	830	990	1 130	1 260
5 "		590	655	720	790	870	1 040	1 180	1 300
6 "		620	690	760	840	920	1 100	1 230	1 350
8 "	610	710	800	880	985	1 060	1 240	1 370	1 490
9 "	650	750	850	940	1 050	1 130	1 310	1 440	1 560
10 "	690	795	905	1 000	1 120	1 200	1 380	1 510	1 620
12 "	750	870	990	1 110	1 250	1 370	1 540	1 680	1 790
14 "	800	930	1 060	1 200	1 340	1 470	1 640	1 780	1 890

30% Rubber Compound. Voltage Test for 5 Minutes. For 30-Minute Test, take 80% of These Figures.

Size.	Thickness of Insulation.											
	3/64	4/64	5/64	6/64	7/64	4/32	5/32	6/32	7/32	8/32	9/32	10/32
1 000 000 to 550 000					4 000	6 000	10 000	14 000	18 000	22 000	26 000	30 000
500 000 to 250 000				4 000	6 000	8 000	12 000	16 000	20 000	24 000	28 000	32 000
4/0 to 1			4 000	6 000	8 000	10 000	14 000	18 000	22 000	26 000	30 000	34 000
2 to 7		4 000	6 000	8 000	10 000	12 000	16 000	20 000	24 000	28 000	32 000	36 000
8 to 14	3 000	5 000	7 000	9 000	11 000	13 000	17 000	21 000	25 000			

made at the works of the manufacturer when the conductor is covered with vulcanized rubber, and before the application of other coverings than tape or braid.

Tests shall be made after at least 12 hours' submersion in water and while still immersed. The voltage specified shall be applied for 5 minutes. The insulation test shall follow the voltage test, shall be made with a battery of not less than 100 nor more than 500 volts, and the reading shall be taken after one minute's electrification. Where tests for acceptance are made by the purchaser on his own premises, such tests shall be made within 10 days of receipt of wire or cable by purchaser.

INSPECTION.

The purchaser may send to the works of the manufacturer, a representative who shall be afforded all necessary facilities to make the above specified electrical and mechanical tests, and also to assure himself that the 30% of rubber above specified is actually put into the compound; but he shall not be privileged to inquire what ingredients are used to make up the remaining 70% of the compound.

DISCUSSION ON "STANDARDIZING RUBBER-COVERED WIRES AND CABLES," AND "COMMENTS ON PRESENT UNDERGROUND CABLE PRACTICE," AT NEW YORK, APRIL 27, 1906.

H. W. Fisher: These papers contain many items of vital interest both to manufacturers and users of high-tension cables. Mr. Langan gives a clear and comprehensive recital of the physical, chemical, and electrical properties of rubber as applied to conductors, but several of his statements are, I think, open to criticism. He says:

> For if there is any one dogmatism to which electrical practice seems unchangeably attached, it is that of a firm belief in the value of a voltage test in determining dielectric efficiency. Yet nothing could be more misleading.

I can not agree with the last sentence, because there is a great difference in dielectric strength in cables that contain different amounts of Para. A compound containing 30 per cent. may have one and one-half to two times the dielectric strength of compounds containing a small amount of Para to which is added a large amount of reclaimed rubber. On account of this fact a voltage test which would not injure a cable insulated with 30 per cent. Para rubber might be sufficient to puncture a cable having a cheaper rubber compound, hence a voltage test can be made the means of determining to a certain extent the quality of the rubber compound. I agree with Mr. Langan that other tests are necessary to determine the true quality of the rubber compound under consideration.

Farther on he says:

> The concensus of opinion, derived alike from theoretical and practical experience, is that rubber is the best of all insulating materials. But in conjunction with other ingredients, and when allied with sulphur, and properly vulcanized, it becomes not only absolutely waterproof, but indeed under normal conditions, one might say, indestructible.

It is a fact that under certain conditions rubber is not the best insulating material. Under voltage stress it will not withstand the continued application of high temperatures so well as some other kinds of insulation in use at the present time. What does Mr. Langan mean by normal conditions, under which he says, "rubber is indestructible"? Rubber certainly deteriorates rapidly under normal atmospheric conditions when placed out of doors.

Regarding rubber-insulated wires for cables, Mr. Langan proposes a 48-hr. immersion in water-test before the tape or braid is applied. I think it would be much better to make the test after these are applied; for in the application of the tape or braid the threads of the cotton are apt to make indentations in the rubber, and consequently a test made afterward would not withstand so high a voltage.

Referring now to the table giving the recommended voltage tests and insulation resistance. Is Mr. Langan prepared to put himself on record as saying that he is willing to manufacture

1 000 000 cir. mils cable with 0.375-in. insulation, and guarantee on every piece an insulation resistance of 3 000 megohms per mile at 60 degrees fahr., the insulation resistance test being made after one minute's electrification and the cables tested within a week after vulcanization? I mention the last condition because it is a well-known fact that the insulation resistance of rubber-covered cables improves with time, at least up to a certain point.

The voltage tests recommended by Mr. Langan are entirely too low. He says:

> That it is the rise in temperature which accompanies a rise in potential, that is so destructive of rubber insulation.

With the proper kind of insulation and the proper voltage test, this rise of temperature should be very small. I have made a calculation which will give an idea of the heat generated by the application of 20 000 volts to a 1 000 000-cir. mil cable insulated with 0.375-in. rubber compound containing 30 per cent. Para. Supposing the electrostatic capacity of such a cable to be about 0.53 microfarads per mile, then the charging current corresponding to 20 000 volts and 60 cycles, will be 3.8 amperes. The apparent energy would be 76 000 watts and, assuming a power-factor of 4 per cent. the watts per mile of cable would be 3 040 or 0.56 watts per foot. The same heat would be delivered by 230 amperes flowing through a 1 000 000-cir. mil cable. Such a current would have very little tendency to heat the cable—especially when it is placed in water—when subjected to the 20 000-volt test. I fully realize that cables insulated with rubber compound of poor quality are not suitable for very high voltages, because such compounds are not so strong electrically and are more liable to become warm under high-voltage tests.

A comparison between the high-voltage tests recommended by Messrs. Langan and Clark shows that those of the latter are at least one and one-half times those of the former. It is my opinion that the tests mentioned by Mr. Clark can be applied without in any way injuring the rubber of a properly designed cable. I do not wish it to be understood that I do not advise the use of rubber-covered cables, because I do for many purposes. The question of cost, however, often precludes the use of rubber. Moreover, there are some very prominent engineers in this country who, because of repeated burn-outs on rubber cables, are rather averse to using them for high voltages.

Scarcely anything has been said about saturated paper-insulated cables for high voltages. Such cables certainly preponderate here, and are giving excellent satisfaction.

In regard to the use of reclaimed rubber, Mr. Clark brings out in an admirable way the fact that in some cases this rubber has to be used to reduce the cost of the cable. With cables for low voltages, 5 000 or below, there is no objection at all to the use of reclaimed rubber, because such cables give perfect satisfaction. Mr. Langan compares the test of a paper cable with that of a rubber cable, the paper cable, of course, being lead-covered and the rubber cable non-leaded and tested in water. He says:

> For this reason it is hardly an exaggeration to say that double the potential imposed on a paper cable is no more exacting than half the amount applied to a rubber cable.

I differ with him in this respect, because when a rubber cable is tested for a high voltage, say 30 000 volts, there is little difference between a test in water and a test with a lead cover over the rubber. The reason for this may be explained as follows: the spark-distance for 30 000 volts is over 1.5 in. in air, and as the specific inductive capacity of rubber is four or five times that of air, the voltage across any air-spaces on the outside of the rubber, caused by defects in manufacture, is sufficient to jump across the air-spaces, heating the rubber there and subjecting the insulation at the weakest points to the total applied voltage, just as would be the case were the cable not leaded, placed in water, and subjected to a test between the conductor and water. The voltage heating effect caused by the discharge across air-spaces mav be the initial cause of subsequent burn-outs. With tests of from 500 to 2 000 volts where the striking distance in air is small, there may be considerable difference between the test of a non-leaded cable in water and the same cable provided with a lead cover. The latter will withstand the highest voltage.

Mr. Clark mentions the use of a pressure-wire for determining the deterioration in the cable. This pressure-wire is imbedded in the strands. I am rather inclined to believe that there would be no indication; for this reason, any moisture that enters the cable would have to go all the way through the insulation and into the strand, and I think that before sufficient moisture gets into the pressure-wire to indicate a low-insulation resistance, the cable would burn out.

Will Mr. Clark explain the apparent inconsistencv in the breakdown voltages in the table? These are 17 000, 19 000, and 18 000 volts respectively, and as the relative amounts of rubber are in the ratio of 1, 2, and 3, the break-down voltages should be least for the first and greatest for the last, by a considerably greater difference than is given. The relative deterioration is verv interesting and significant.

H. G. Stott: The condition of specifications for rubber-covered cables is an extremely chaotic one at the present time. Every engineer has his own specifications, and the result is that we are almost entirely dependent upon the honesty of the manufacturers in building these cables. In trying to determine some approximate method by which we could make specifications for rubber-covered cables, I obtained from one of our manufacturers a number of samples of rubber-covered wire. These wires were No. 10, covered with $\frac{3}{32}$ in. of rubber, having

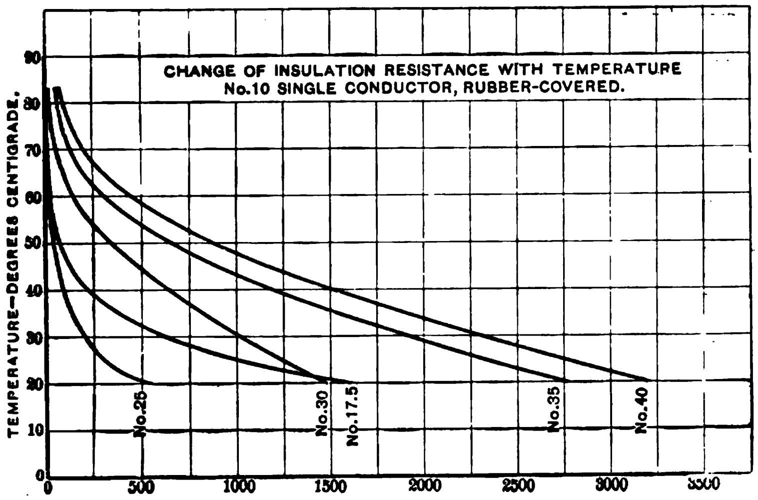
CHANGE OF INSULATION RESISTANCE WITH TEMPERATURE
No.10 SINGLE CONDUCTOR, RUBBER-COVERED.
TEMPERATURE—DEGREES CENTIGRADE.
90
80
70
60
50
40
30
20
10
0
No.25
No.30
No.17.5
No.35
No.40
0
500
1000
1500
2000
2500
3000
3500
MEGOHMS PER MILE.

Fig.1

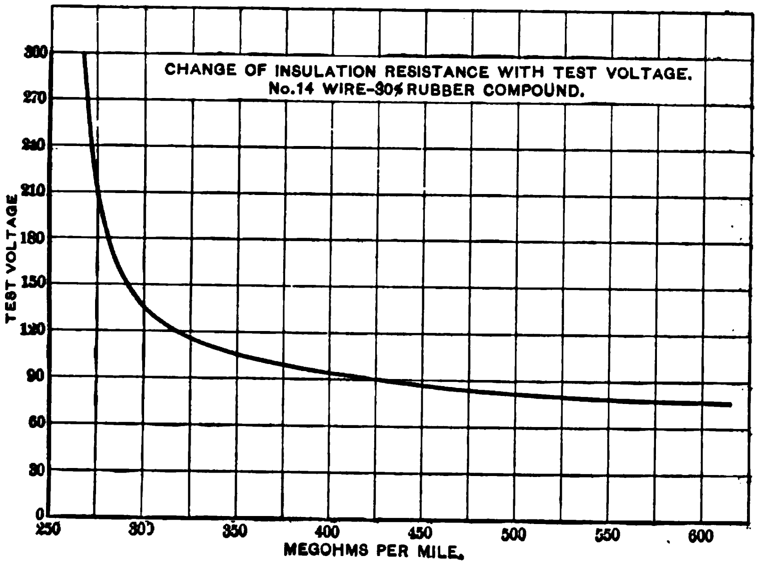
CHANGE OF INSULATION RESISTANCE WITH TEST VOLTAGE.
No.14 WIRE-30% RUBBER COMPOUND.
TEST VOLTAGE
300
270
240
210
180
150
120
90
60
30
0
250
300
350
400
450
500
550
600
MEGOHMS PER MILE.

Fig.2

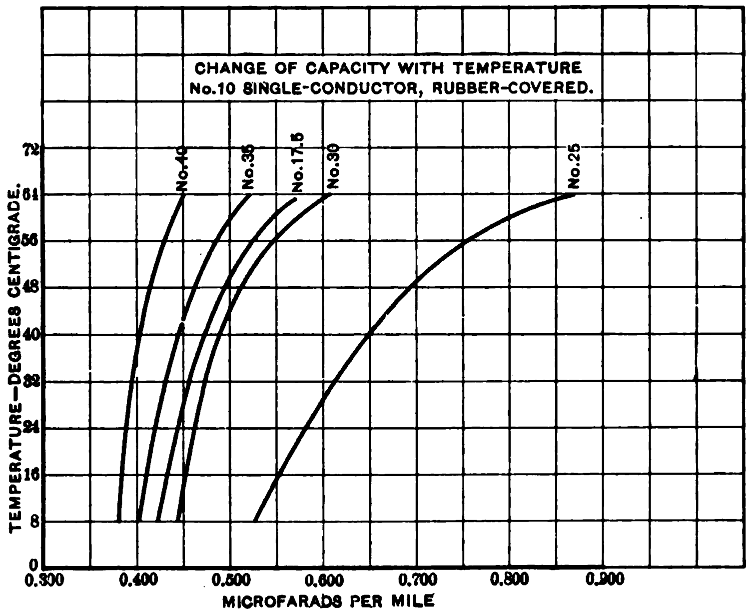
CHANGE OF CAPACITY WITH TEMPERATURE
No.10 SINGLE-CONDUCTOR, RUBBER-COVERED.
TEMPERATURE—DEGREES CENTIGRADE.
72
64
56
48
40
32
24
16
8
0
No.40
No.35
No.17.5
No.30
No.25
0.300
0.400
0.500
0.600
0.700
0.800
0.900
MICROFARADS PER MILE

Fig. 3

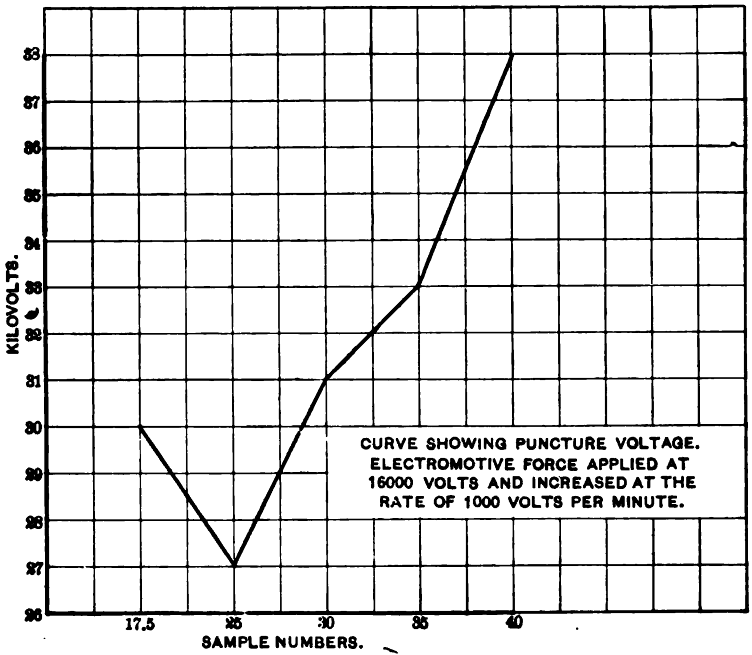
KILOVOLTS.
38
37
36
35
34
33
32
31
30
29
28
27
26
CURVE SHOWING PUNCTURE VOLTAGE.
ELECTROMOTIVE FORCE APPLIED AT
16000 VOLTS AND INCREASED AT THE
RATE OF 1000 VOLTS PER MINUTE.
17.5
25
30
35
40
SAMPLE NUMBERS.

Fig. 4

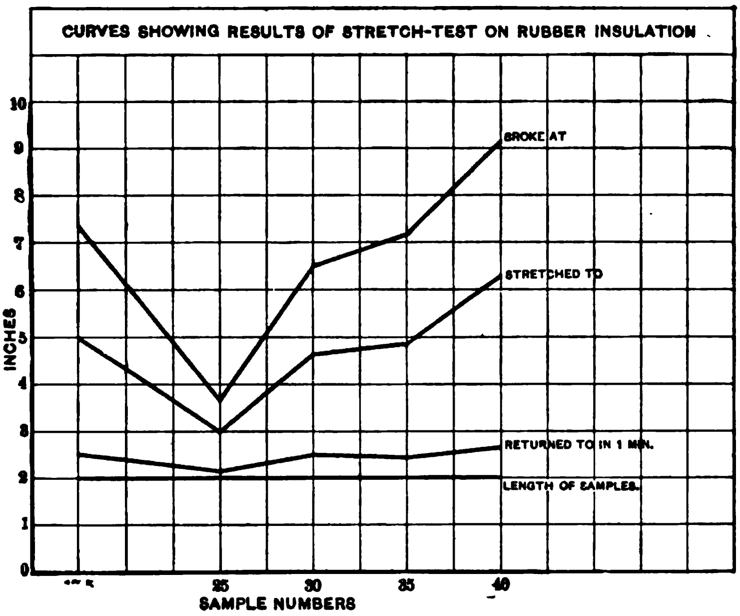
CURVES SHOWING RESULTS OF STRETCH-TEST ON RUBBER INSULATION
10
9
8
7
6
5
4
3
2
1
0
INCHES
BROKE AT
STRETCHED TO
RETURNED TO IN 1 MIN.
LENGTH OF SAMPLES.
25
30
35
40
SAMPLE NUMBERS

Fig. 5

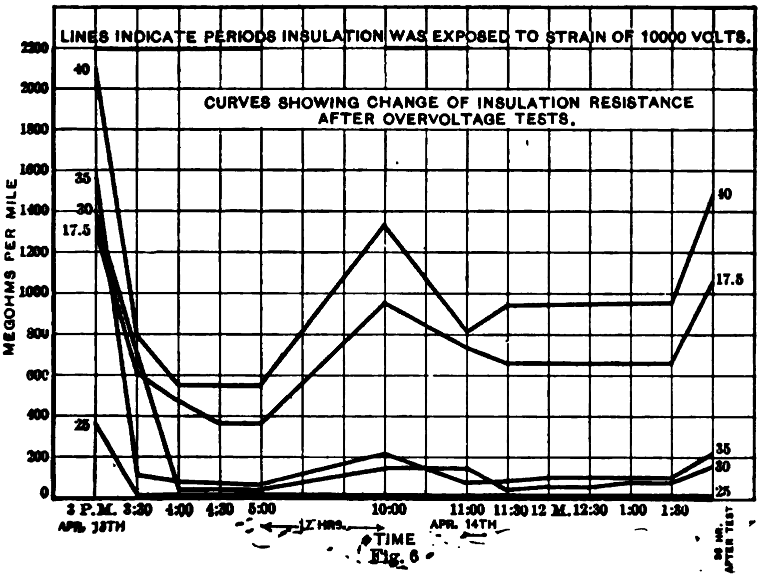
LINES INDICATE PERIODS INSULATION WAS EXPOSED TO STRAIN OF 10000 VOLTS.
CURVES SHOWING CHANGE OF INSULATION RESISTANCE AFTER OVERVOLTAGE TESTS.
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
MEGOHMS PER MILE
40
35
30
17.5
25
40
17.5
35
30
25
3 P.M. 3:30 4:00 4:30 5:00 10:00 11:00 11:30 12 M. 12:30 1:00 1:30
APR. 13TH
17 HRS.
APR. 14TH
TIME
20 HR. AFTER TEST

Fig. 6

various percentages of Para. These tests were carried out for me by Mr. Chellis. I would like to show the results of these tests and give some illustrations.

The results obtained in Figs. 1 to 7 are summarized in Fig. 8; they show conclusively how difficult a matter it is to draw up any specifications which will ensure any specified amount of Para in a rubber compound.

It can be seen how readily a manufacturer who wishes to use reclaimed rubber can provide a cable which will show up better than a cable containing the specified amount of Para, by introducing a large amount of reclaimed rubber and thereby getting a very cheap compound. From these tests it would appear that the variation of insulation resistance due to change of temperature is the best measure we have at the present time of the amount of Para in the compound. The puncture test is also helpful, but not absolutely, because these two, 17.5 and 25, change places; however, we have the 40, 35, and 30% in their proper places. The stretching test is absolutely unreliable, but the variation of insulation with voltage test, which is in itself more or less a puncture test, is apparently an indication of the amount of Para.

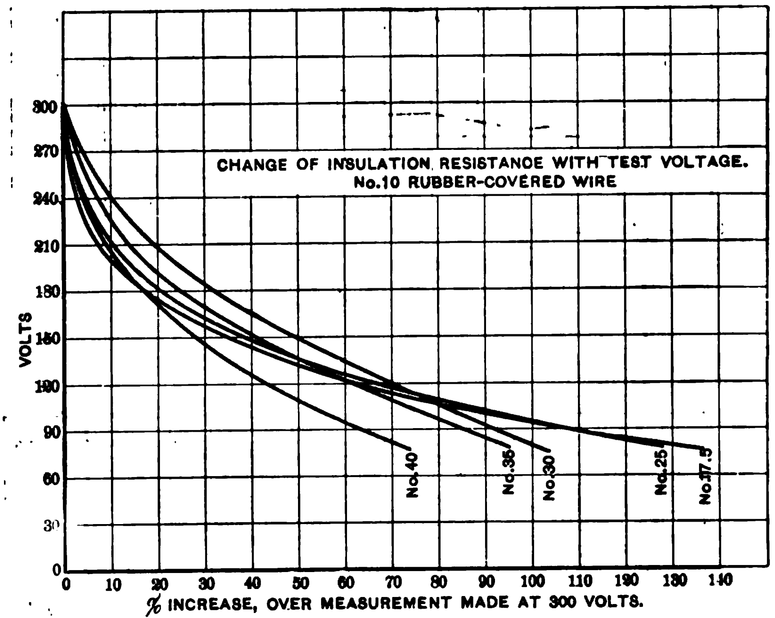

Fig.7

Wallace D. Clark: In the 25, 30, and 35, the other matter was all dry mineral matter, and the same compound in each case?

H. G. Stott. Exactly the same compound in each case.

John Langan: Were those cables chemically analyzed, even the 17.5, for the acetone test?

H. G. Stott: They were all chemically analyzed, but not with the acetone test.

Mr. Langan: That is the important one. I should like to see the chemical analysis of the 17.5. The chemical analysis is the trying one, the acetone test particularly. I think you will find a very large variation on a proper chemical analysis, in the case of the 17.5 per cent. of rubber and 40 per cent. of shoddy.

Mr. Stott: My experience is that the chemical test is valueless.

Number of Sample	40	35	30	25	17.5
Insulation Resistance, 20° cent.	1	2	4	5	3
Insulation Resistance, Temperature Coefficient.	1	2	3	4	5
Capacity.	1	2	4	5	3
Capacity, Temperature Coefficient	1	2	3	5	4
Puncture Voltage.	1	2	3	5	4
Stretch Test	1	3	4	5	2
Dielectric Time Strain Test.	2	3	4	5	1
Change of Insulation Resistance with Test Voltage.	1	2	3	4	5
Cost of Compound	5	4	3	2	1

FIG. 8.

Philip Torchio: The problem of standardizing rubber-covered cables and wires is a difficult one, and I hesitate to make any criticism that might be construed to be antagonistic to a movement of this kind, because, as a matter of fact, the whole electrical industry is vitally interested in this subject. It is still a desideratum in the electric lighting and power companies to see developed and put on the market a cheap and reliable system of house wiring which will reduce the first cost of installation thereby leading to an increased demand in a field where first cost is now an almost insurmountable difficulty in obtaining business. Practically the same conditions exist in other electrical applications, creating a large class of consumers all clamoring for cables and wires as cheap as can be secured consistent with reliability and safety. On a very much smaller scale, however, there is a demand for a different class of cables used in connection with extra high voltage installations, for which condition the question of cost is rather secondary to the foremost and important requirements of high dielectric strength of the insulating material and durability and life under varying conditions of temperature.

These requirements apply mainly to wiring inside of buildings. Outside of these requirements there is a very large field for use of cables for underground transmission and distribution of high- and low-tension current. For this purpose, paper-insulated cables have been used in the majority of cases in preference to rubber-insulated cables, mainly on account of the first cost, especially in the case of high-tension systems where the insulation cuts a big figure in the total cost of the cable.

Discussing the proposed specifications for rubber-insulated wires and cables for the two classes of requirements mentioned above; namely,

1. Low-tension wires and cables for the inside of buildings and stations.
2. High-tension rubber-insulated wires and cables.

For the first class of cables the dielectric strength and insulation requirements are of secondary importance to durability. The high-tension cable, on the contrary, requires high dielectric strength and moderately high insulation resistance, and also durability, under conditions of temperature sometimes very severe. What is desirable to obtain in a wire or cable is mainly durability and life in common for all classes of wires and cables, and a moderately high insulation resistance and high dielectric strength for high-tension cables.

The proposed specifications presented to-night take it for granted that a wire or cable insulated with 30 per cent. of pure Para is the best insulation that can be used for all rubber-insulated wires and cables. I am not inclined to doubt the effectiveness of cables made under these specifications, but I know from personal experience that for a certain class of requirements cables built with less than 30 per cent. of pure rubber, mixed with other ingredients, will give a product of the same durability and same general satisfaction as a 30 per cent. rubber cable, and save the purchaser a considerable percentage in first cost.

I will not say that all manufacturers use less than 30 per cent. Para in their cables and wires, but I am certain that some of them do; and as long as they supply these wires and cables for the legitimate demand of purposes warranting engineers and contractors to make use of them, I do not see why the INSTITUTE should try to stop it. I think that the

INSTITUTE cannot possibly compel a change of this kind, because the existing conditions are created by a cause beyond the INSTITUTE's control—competition. But granting that it would be desirable to standardize the rubber-insulated cables by specifying 30 per cent. pure Para, how could it be accomplished?

In brief, the papers recommend two tests: one, the acetone test, to determine the percentage of extractive matter in the compound; the other a mechanical test of elongation and tensile strength. One of the papers recommends a limit of 5 per cent. of extractive matter of *the total compound*, the other 6 per cent. With these percentages it is proposed absolutely to prohibit the use of less than 30 per cent. fine Para in the compound. I regret that Mr. Langan has not more clearly stated the fact that it is impossible at the present time for any chemist to determine directly the amount of pure Para in a compound. He must arrive at this amount by inferences and assumptions, by means of which he tries to assume how much of the rubber found in the compound is pure Para and how much is inferior rubber. With the 5 or 6 per cent. extractive matter limitation of the specifications, any manufacturer can use almost anything between 30 per cent. and nothing of pure Para and still meet the specifications as to the 5 per cent. limitation. Five per cent. of the total compound is what is called for in the specifications. In a pure Para, that is 1 per cent. of extractive matter, and 1 per cent. of 30 per cent. would be only one-third of 1 per cent. I should represent the extractive matter in percentage of the total amount of compound. Of course in vulcanization it is true that about 3 per cent. of extractive matter is added by the process of vulcanizing, and that would add about 1 per cent., not 5 or 6 per cent. of the total per cent. of the compound, for 30 per cent. pure Para.

I have not had sufficient personal experience to enable me to say much as to the value of the mechanical tests. The United States navy has specified these tests for the last two years, and as their specifications call for 40 per cent. pure Para. I think they are justified in so doing for obtaining the satisfactory results which they must secure under peculiarly difficult conditions of transacting business.

I have no doubt that elongation and tensile strength tests will give valuable information. I should, however, hesitate to purchase cables on specifications based upon tests of this character, as I do not believe there is sufficient information available to arrive at definite conclusions.

I would say in connection with the figures given by Mr. Stott that the results of the elongation and stretch test might have been considerably affected by the process of vulcanization. In making a cable it makes a great deal of difference how the compound is vulcanized: it may be under-vulcanized resulting in a mucillaginous product which has no strength; or it may be over-vulcanized and will break easily.

H. G. Stott: How can yon tell that ?

Philip Torchio: You can get the same results of the table for different samples with the same per cent. of Para in the compound by varying the temperature of vulcanization.

H. G. Stott: How can you tell after it is manufactured ?

Philip Torchio: I mean to point out that the discrepancy you show might not be entirely due to the condition of the 17.5 per cent. of Para and the 42 per cent. of shoddy reclaimed rubber. It may be due to over-vulcanizing in one case or another.

Summing up the criticism of these proposed specifications, I should think that they could be properly made the foundation for the work of a special committee of the INSTITUTE, to whom should be given the power to investigate and collect data on the subject and make a report to the INSTITUTE at some future date. I suggest that this committee communicate with the English association of cable makers to obtain their experience along the lines which led them to manufacture two types of rubber-insulated cables; one marked as Association Cables are standardized as to grade and other physical dimensions, and for these only the best rubber is used, the quantity to be varied according to the grade and the necessary ingredients added according to the experience of each manufacturer; the other marked Non-Association Cables, and are built with cheaper compound, for which cables there is a legitimate demand for certain purposes. The Association cables are marked with a yellow label and the Non-Association cables with a green label, attached to each coil by a tape secured with a lead seal.

I would add in connection with the specifications in the papers, that to guarantee the life of the compound a voltage test should be specified where it is possible for, say, double voltage, to be applied after three or four years' service. This opens up the great objection that misuse of the cable may deteriorate the compound; but that is one of the many difficulties in the whole proposition.

A. E. Kennelly: The papers before us do not seem to attribute sufficient importance to breakdown or dielectric strength tests. It appears to me that the construction and operation of a high-tension cable resemble the construction and operation of a bridge. There are electric forces to be withstood in the cable, depending upon the gradient of volts per radial centimeter, just as there are mechanical forces to be withstood in the bridge structure. We have to employ dielectrics whose minimum strength by breakdown test is so many kilovolts per centimeter, and we should seek to employ a factor of safety of at least three. The greatest dielectric stress accompanies the greatest curvature; that is, at the inmost layer, in contact with the conductor, and the stress rapidly diminishes towards the outside layers, where it is least. The practical question before the purchaser of a cable is how to secure a total safe dielectric strength to withstand the working voltage plus that amount of elevation due to incidental surges which cannot be entirely avoided. But the engineering questions behind this are the dielectric strength of the material, the maximum working stress, and the factor of safety, together with the durability of the insulating structure; just as in the case of a railroad bridge we have to rely upon the tensile strength of the steel used, the maximum working stress, the factor of safety, and the durability of the steel.

Although 30 per cent. Para rubber cables have given good satisfaction, it seems illogical to assume that specifications must always be drawn to obtain this particular percentage of that geographical type of this substance. Surely the problem is much broader. What we need are plentiful observations of the dielectric strength of definite insulators of all kinds, at different ages of service, and under different kinds of treatment during service. It is of course out of the question to stress cables in satisfactory service to the breaking-point in order to satisfy curiosity as to their breaking strength; but let pieces be ruptured, from time to time, to give indication as to the dielectric strength that a cable may be expected to possess.

The very high tension cable of the future seems likely to be a composite cable of successive layers of different insulating materials, commencing with the dielectrically strongest, and terminating externally with the cheapest and dielectrically weakest. But surely the key to the problem lies in dielectric strength as measured by the breakdown test. In comparison with dielectric strength tests, mechanical tests and insulation resistance tests are merely subsidiary.

E. W. Stevenson: On the second page of Mr. Langan's paper he makes a strong objection to the rule laid down by the N.E.C., relative to the dielectric strength of the 3 000 volts per $\frac{1}{64}$ in. thickness of insulation. This point has been brought up so frequently that it has been supposed to be generally understood. I made the same mistake when the rule was first issued, and while I still have some objections to it, I don't think the rule is so far fetched as Mr. Langan seems to think. For instance, the pressure is only supposed to be applied to one foot of submerged wire, and I think it would be a very poor wire that wouldn't be able to stand it. I have found in many instances that lengths of 500 ft. of No. 14 B. & S. copper, covered with $\frac{3}{64}$ in. wall of the most ordinary cheap compound, able to stand 9 000 volts and even more. This statement is not made in favor of the rule, because I think that a better rule than this one could be made to cover this point.

The statement that the pressure test is no criterion as to what a good insulator is, is rather startling. But I really can not see why if a cable is " doped " and afterwards taped and braided or lead-encased, this dope should not last indefinitely and be just as good as the insulation itself; but I do agree that the pressure tests should be combined with at least one or two other tests to verify what the former shows.

I think all transmission engineers will agree with me when I say that in extreme high tension transmission and heavy power work, paper has almost entirely supplanted rubber. Both have their special advantages, but I think I am quite sure in saying that more than 75% of high-tension power distribution is now and will in future be confined to paper insulation.

Mr. Langan's remarks about vulcanization will give engineers an idea of the care that has to be taken in this particular process to insure proper covering. In commenting on the different kinds of rubber, I think he places the fine Para in rather too exalted a position over some of the others. There are many good qualities of rubber that give excellent results, and these rubbers can not be ignored by manufacturers.

To my mind the mechanical tests are of the greatest importance, and if purchasers would be careful to specify some such requirements they would be sure of getting a good article. I am rather inclined to think, however, that the acetone extract is excessive, as it is well known that 5% will allow a considerable proportion of inferior rubber, and this extract should not be any more than 4, or 3.5 would be better. Considerable care must be taken in making such a test, as the Soxholet extractor, the apparatus generally specified, in the hands of one not thoroughly familiar with its operation is likely to give inaccurate results. The temperature of operation, the time and quality of ingredients used, must be so carefully watched that one must be thoroughly familiar with all these points in order to assure himself that the results are correct. However, I quite concur with Mr. Langan that the chemical analysis is not always practicable, and that fairly good results can be obtained from the mechanical tests. But I am rather inclined to doubt his somewhat close return. He speaks of a return of to within 25% after the sample has been stretched to three times its length; this I think can safely be modified to within 50%, as there are many instances in which perfectly genuine 30% Para will not do better.

I do not quite see the logic of his statement that if a 30% compound of fine pure Para will be quite successful in meeting all the requirements he specifies, why manufacturers should be tempted to put in 15% of pure Para and 30% of a cheaper grade, as in the former instance with pure Para at $1.50 per pound and others at $1.00 per lb. the compound will cost 53 cts. per lb., while in the latter he will get a compound at 58 cts. per lb., or in other words the imitation compound will cost him 12% more per pound than the genuine and I don't think any manufacturer would be foolish enough to throw money away in that manner, except probably that the latter compound would have a greater covering capacity than the former, but even then I think he would lose at least 5%. There is also reason to question the statement about an analysis showing the different percentages of Para and other rubber, as I don't think there is a chemist

who could do it. Extractive matter varies with the period of vulcanization and can not show percentage.

In the table are shown figures for specifications on high-grade wires. To me these seem very curious. For instance, in spite of the statements about some of these wires being able to stand fairly high pressure, no more than 1 000 volts is allowed to be put upon any of the sizes on low tension. Compare these figures, taking for instance the relative wall on sizes 14 to 8 B. & S.; the wall is $\frac{3}{64}$ in., or in other words 46 mils. At present the National Code people call for 1 500 volts on this size on any compound that happens to be on it, whereas for high-grade work this table only calls for 1 000. Now a telegraph specification, on their office wire No. 16, with an outside diameter of 0.125, or in other words a wall of 37 mils., demands 2 000 volts, and while I do think that this latter is excessive, I must say I think that 1 000 volts is very low for such grade of compound, and there is no reason at all why the National Code figures cannot be used, at least on lower sizes. The incongruity of these figures can be further seen by referring to the second table of medium tension. The wall of insulation on the same size of copper is $\frac{3}{32}$ in.; or, in other words, twice the low tension, and yet the pressure test is five times as much.

While admitting that a high quality pure Para has a high initial dielectric resistance test, I do not see any reason for Mr. Langan's statements that the high dielectric resistance in megohms per mile is any positive proof that the compound is of first-class quality. In the course of the last few years I have had occasion carefully to test many samples of wires, and I have found that samples of wire having a very high dielectric resistance have not always been either the best pressure resisting or the best mechanically.

On the other hand, I know of another wire which has a dielectric resistance test of only 400 megohms per mile, a sample of which, about 500 ft., was lying around for many months in the factory and probably tested to 11 000 and 12 000 volts one hundred times during that period, and withstood it to the end. Mechanically this compound had a good stretch, but it had rather a slow return. However, it got there in time within 50% of its original length.

My object is to show that there is no reason why compounds showing a lower dielectric resistance should not be just as good for life or pressure tests as are Mr. Langan's, and I would like to suggest that a committee, chosen from those who could competently investigate this, should be formed in order to settle this question.

For some time I have been trying to eliminate the, to me, rather curious method of stating how many megohms per mile different sizes of wire should stand. In many sheets showing such figures the calculations are at fault. For instance, take the National Code wires as they stand to-day, and their requirements. The No. 14, $\frac{5}{32}$ in. calls for 200 megohms per mile, while 1 000 000 cir mils with an insulation of $\frac{7}{64}$ in. calls for 100 megohms, or half as much as the No. 14, whereas the simplest arithmetical calculation will show that it ought to be one-fifth. The rule for dielectric resistance is megohms per mile at 60° fahr.—coef. X Log. D/d, D standing for the outside diameter of the insulation, while d is the diameter of the copper. This formula has been used ever since the old Hooper days, way back in 1860, and a very carefully worked out table can be found in Munro & Jamieson's pocket book, also I think in Clarke & Sabine.

The use of the formula would simplify matters very much, and while the figures given show a coefficient of about 13 000, I think the adoption of a figure somewhere in the neighborhood of 5 000 to 6 000 would be quite sufficient. I suggest the following formula: Megohms per mile after one minute electrification at 60° fahr.—Log. $D/d \times 6\,000$ or $6\,000$ (log. D—log. d).

D = diameter of insulation. d = diameter of copper.

I quite concur with the statement that excessive pressure test is unnecessary and dangerous, but I think Mr. Wallace Clark's rule, stated in his article before the National Electric Light Association, of 2.5 times the working pressure, is quite within safe limits, and this is generally understood all over the country. However, there is no objection to Mr. Langan's rule of double the working pressure.

Townsend Wolcott: There are different ways of determining the amount of rubber put in a compound. The Signal Corps has found that the best way is to have an inspector at the works and see the compound mixed. The determination of the amount of rubber by the acetone extract is a very uncertain matter, and the chemists seem to be divided into two classes; those that say that Para rubber never has more than 2 per cent. acetone extract, and those that find it is more in certain cases. I have an analysis here made by a chemist in whom I have a great deal of confidence, in which one sample gave acetone extract of 3.76; the lowest sample gave 2.03.

The rubber, even of the purest varieties known to commerce, is not a definite chemical compound. The compound, $C_{10}H_{16}$, which is the valuable ingredient, may not constitute the whole of what is left, even after the acetone extract is made. The relative values of the four samples analyzed were given by this chemist, adopting one sample of rubber as an arbitrary standard, in the same way that Matheissen adopted the standard for copper. The values vary from 88.60 to 101.67 per cent.

Durand Woodman: I have been interested in the subject of rubber insulation for five or six years and have done considerable chemical work on it. I am much interested to hear the results of some of your electrical and physical tests, but am disappointed in the apparent unreliability of the " stretch test. I have been told lately—and I think some one has said the same thing to-night—that chemical tests are absolutely worthless. I doubt very much whether any one who has had great experience with the chemical test would concur absolutely in that opinion. My own opinion is that when a set of specifications is finally adopted, it will include electrical tests, physical tests, and some chemical tests. The subject needs a good deal of discussion by those who hold opposite views.

There is one point that has almost escaped attention, and that is the percentage of extract obtained by treatment with acetone. The limits mentioned, 5 or 6 per cent. on the total compound, would mean when calculated on the rubber used, if you use 30 per cent., from 16 to 20 per cent. from the rubber. It is therefore necessary to consider very carefully whether you want to adopt such a figure as 5 or 6 per cent. of acetone extract, as that would certainly allow the use of rubbers that are not Para. In regard to the time of the chemical analysis, that may be considerable or it may be little, depending on the extent to which it is carried. The acetone extract, if it is desired, can be done in a very few hours; that is to say, a sample submitted one day can be reported on the next day, or even in less time, but I do not believe in hurrying these matters too much. I should say 24 hours would give a reliable report as to the acetone extract. A few other points are obtainable by the acetone extract; for instance, the amount of free sulphur; and while manufacturers are no doubt more careful than they used to be in regard to that, it is undoubtedly a thing which should be controlled by the specifications, as free sulphur is something that is subject to constant change by oxidation and shortens the life of the rubber.

Wm. McClellan: The two features of insulation in which we are always interested, are; first, its ability to do the work for which it is designed, and, secondly, its durability. It is in this latter quality that all the difficulty comes.

Experience shows that while there may be other substances capable of providing an adequate and durable insulation, rubber is at present the only substance worthy of confidence. But as is well known, rubber alone will not provide a durable insulation. It must be mixed with other material. Now the proportion and quality of rubber and the nature of the other substances combined with it determine the character of the insulation.

The point cannot be made too plain, that according to the use to which the insulation is to be put the percentage and quality of rubber may vary to advantage over comparatively wide limits, and the nature of the other substances may vary to advantage also. For a large proportion of the work that is to be done, 30% pure Para is wholly unnecessary, and much too expensive; moreover, there is a large amount of very good rubber produced, not so fine as Para, but of the greatest use in the art of insulation. Now, a specification to be standard should be put in such a form as to permit the use of any percentage of any kind of rubber which the intelligent engineer may desire. Any specification which calls for 30% pure Para uniformly, without regard to the particular use for which the insulation is designed, is fundamentally bad from an economic standpoint. It would frequently compel us to use a much more expensive insulation than is necessary, and it would deprive us of using many other rubbers which possess great merit, though not so great as fine Para.

Unfortunately, however, as has been shown very clearly tonight, there is no test which is absolutely reliable in showing the percentage and quality of rubber in a compound; all tests proposed are indicative only, and must be used with the greatest caution.

As has been shown, the acetone test is positive in determining the quality of crude rubber; this test, however, is not applicable to rubber compounds, because very frequently the insulation manufacturer desires to introduce other substances with the rubber which contain in themselves extractive matter. Therefore the extractive matter in a compound is absolutely no guide in determining the amount of rubber in the compound, unless the specifications limit the substances which may be introduced into the compound; in other words, it is proposed to run the risk of requiring a more costly and less durable insulation in order that the acetone test may be applied to a rubber compound. It seems unnecessary to state that such a proposition approaches the whole matter of standard specifications from the wrong direction. In the specifications proposed by Mr. Langan the implication is made that if the extractive matter becomes more than 5 or 6% the insulation will be bad; whereas, as a matter of fact, for many purposes the extractive matter could be considerably higher and a durable insulation obtained.

The object of a specification is to define just what is wanted in such a way that all persons using the specification can supply the article needed, and so that the purchaser can determine that he is getting just what he called for. We can have a standard specification, but we can not have standard rubber insulation for all purposes any more than we can have a standard steel for all purposes. The speaker does not propose to write a set of specifications, but he desires to suggest a certain norm as a basis for rubber insulation specifications, which seems to cover the above points. In brief these are:

1. Clauses fixing copper conditions.
2. Clause fixing quality of rubber to be used, by stating limits of extractive matter.
3. Clause fixing percentage of above-mentioned rubber to be used, the mixing to be done in the presence of purchaser's

representative. Only general specifications as to other material.

4. Clauses covering sheath, braid, etc.
5. Clauses covering mechanical, electrical, and sulphur tests.
6. General clauses in regard to tests, apparatus, etc.
7. Clauses covering packing and shipping.

A specification based on the above norm would seem to have merit because:

(a) It makes it possible to make use of all qualities of rubber, in varying percentages, to suit the use to which the insulation is to be put.

(b) It puts the extractive matter test where it belongs; that is, on the rubber itself. It puts no hardship on the manufacturer, nor demand to know all his business; but on the other hand allows him all freedom in proper experimentation, and does not stifle progress. Moreover, it puts a premium on the good name of the manufacturer. The principal value of the mechanical and electrical tests under this system is to determine that the application of the compound to the wire has been properly made.

(c) It gives positive assurance that the purchaser is getting just what he called for. In a short time at the factory the purchaser's representative can see the rubber weighed out and the compound mixed. This is all he need wait for, because by taking with him a sample of the rubber and a sample of the mixed compound he has a positive check that there is later no substituting of a poorer compound by the manufacturer. The acetone test is particularly valuable here, since there is no way for further extractive matter to get into the material, except the slight increase at vulcanization which can easily be allowed for.

It is of course true that such a specification is more elaborate, and a little more expensive to carry through than some of the others, but careful investigation will show that this is not so to a very great degree; moreover, as in any specification, the purchaser is at any time justified in waiving his rights to certain tests if the amount or quality of what he is purchasing does not warrant him in going to the expense.

J. B. Taylor: There is one point in connection with the installing or testing of high-voltage cables that has not been referred to, and that is the ability of a cable, with insulation of rubber or other material, to stand a temporary high potential. Cables have to stand for 24 hours a day a certain normal potential strain and generally stand it well, except when trouble develops at joints or other places where it is improperly handled. Then comes a surge. I think the troubles and damages caused by surges are over-estimated; but there is no doubt that any system will occasionally have abnormally high potential for a very short period of time.

It has been brought out that the element of time is of importance in connection with high-potential test of cables. In some cases the time specified is 30 seconds, and in other cases half an hour, or even an hour. We should know if the cable that stands double potential for 30 minutes will stand 50 000 or 100 000 volts for one-tenth of a second.

C. F. Scott: It seems to me that the discussion this evening is distinctly from the standpoint of the manufacturer; it is a discussion of the methods and materials used in manufacturing cables. Now the cable is for use, and as some one has remarked, the real essence of a cable test should be to determine its reliability. For other kinds of apparatus we do not necessarily specify the materials and how they shall be made and treated in the course of manufacture; we deal with the final results. There was a time when consulting engineer's specifications for dynamos went carefully into the amperes per square inch and the induction, and things of that sort. Now specifications for machinery are based upon the final results, upon tests of those elements which go to make up and determine the performance of the machine in service. In high-tension tests for other kinds of apparatus, it is the custom in general practice as is laid down by the standardization rules of this INSTITUTE, to depend upon certain high-voltage tests which in general are twice the working voltage. Can the cable accept the same kind of a specification, the same limits, or must it have some other kind of a specification and some other kind of limits? Must a man who wants a cable for a given service necessarily specify the ingredients of that cable and then go to the manufacturer and see that they are actually put in and stirred up and baked properly, or is there some way to determine whether the cable is going to do the required service? If the high-tension test is to be applied, shall it be the same as for all other apparatus or shall it be something considerably less? That matter was up for discussion at a meeting of the Standardization Committee recently, and it was seriously proposed that the test on cables should be considerably less than the test on transformers. To the operating man that would mean that the transformers are more reliable than the cables, and that some point in the cable would likely be the point of breakdown.

The time element of the test is very pertinent. One minute has been proposed. A cable is not likely to receive double voltage for a minute; it is much more likely to receive a very high voltage for only a fraction of a second. What is the relation between the strength of the cable and different voltages for different times? and would it not be fairer and better as determining the operating characteristics of the cable to make a higher voltage test for a shorter time?

It is obviously desirable to have means of testing a cable at the time of its installation, and subsequently, which will indicate the suitability of that cable for meeting the service conditions to which it will be subjected. It is desirable that the test should be independent of the materials and methods employed in manufacture. It seems to be well established that the same kind of high-pressure tests which are applied to other apparatus are not wholly satisfactory for cables. One who is not an expert on the subject of cables, but who takes a general view of the subject, must come to the conclusion, judging from the present papers and discussion, that the views with regard to the matter are quite divergent and unsettled.

H. W. Fisher: In one of Mr. Stott's diagrams, he shows that the insulation temperature coefficient varies in the order of the amount of Para rubber. I have made several tests in which this does not occur, and therefore I think that this rule should not be relied upon for determining the rubber compound. He also says that the insulation resistance is affected by the voltage of the battery. I know positively that this is not always the case. I have made tests where the voltage varied from 50 volts to 300 volts, in which the insulation resistance was practically the same, and I think that some of the peculiarities he noticed in these tests was due to the fact that the wire was small and had only a small amount of rubber. I think if you will make tests on 000 or 0000 with $\frac{4}{32}$ to $\frac{6}{32}$ rubber you will get quite different results.

Philip Torchio: In regard to the effect of high-frequency voltage tests on cables. From tests made abroad it was found with a frequency of several thousand alternations that the cable broke down at about twice the voltage, than at 50 cycles.

President Wheeler: I am quite surprised to find that cable specification is in the unsettled, and rather difficult-to-settle condition that it is. I think I see an opportunity for the INSTITUTE to do something, and I suggest to the Secretary that at the meeting of the Standardization Committee to-morrow he call their attention to this discussion.

I think a committee had better get right to work and devies methods by which the matter shall be handled. If there is one thing important above all others in engineering, it is standardization. It is hard to do all the things we want to do, but let us agree beforehand what those things ought to be. I am glad to see the tremendous growth of the cable business and to see how the preparing and laying of cables has now become a matter of course. While I do not intend to speak about the cable subject, I am not altogether unfamiliar with it, because some time ago I was the equivalent of the electrician of this city. From 1888 to about 1895, I had the duty of getting the overhead wires in New York underground, as probably most of you remember, and all the wires got between the Commissioner of Public Works and myself, and they came down. The discussion this evening reminded me of the fact that when the companies were asked to take the wires down they practically said they could not make cables that would carry the electric current underground. Several cables were put underground and they sat up nights watching them. Then more cables were laid, and for two or three years a long and voluminous series of reports, with megohms and all sorts of things per mile in them, were sent to me and I was supposed to read them all and to see that all these cables that had been laid were kept up to the mark. It got to be a mere routine, because the companies which did the work did it beautifully, and the company which dug the subways and tested these cables saw that they did not burn up the subways, and these reports became unnecessary.

John Langan: Many of the speakers to-night seem to have missed altogether the import of the paper under discussion. The paper relates specifically to the standardizing of rubber-covered wires and cables. As it is to-day, there is no standard. Ask any engineer of prominence here in New York to get up a set of specifications for rubber-covered wires and cables and he is at sea how to compel good results.

If voltage is a certain criterion, as some of the gentlemen affect to believe, why are they at their wits' ends trying to improve the character of rubber insulation? Why is the Standardization Committee trying to improve the rubber insulation if the voltage test is a criterion? Here is a curious illustration: send out proposals for a thousand feet of No. 14 wire code, and send out afterwards proposals for a thousand feet of No. 14 wire 30 per cent. Para rubber, and the difference in price will amount to 50 per cent., notwithstanding the fact that the voltage tests in the first place are very exacting. Why is this? Because the amount of rubber, which the tests in the latter case compel, compels also an increase in price. This shows that the commercial price, where the tests are enforced, indicates the character of the compound.

Mr. Stott has contributed a great deal of interest to the discussion to-night. The curves and tabulations which he exhibited are extremely interesting, and as much of a revelation to me as to any one else, that he could, in so short a time, disclose so much valuable information. These curves prove, on the whole, the statements I have made of the means by which to standardize tests. The only drawback to them is that the 17.5 compound, with its ups and downs, is as fluctuating as the stock market, and is undoubtedly off in some particular. Before you can determine anything about a compound, you must submit it to a chemical analysis, and know exactly what it contains.

It should be borne in mind, however, that this compound has 60% of unidentified rubber in it, and it is perfectly conceivable that, initially at least, this might show a test as high, if not higher, than 25% of Para. And it was to meet and offset just such a contingency as this that the rubber in the specifications was limited to 32% of fine Para.

To supplement Mr. Stott's curves—this is the laboratory from which I deducted the tests referred to in the paper (Mr. Langan exhibits a number of specimens of pieces of rubber-covered cables and wires). These samples represent all the manufacturers on the American market; they do not apply to any particular one, but to all. Here is a piece of wire containing 40 per cent. Para rubber. You can see it is almost impossible to break it. Here is another containing 25% of ***rubber***, as distinguished from *Para rubber*. See the difference; it has some tensile strength, but very little It is about a year old. Here is a piece of code wire that a certain gentleman has eulogized to-night which is, as you can see, destitute of strength and tenacity. In making these tests bear in mind that I was trying to get at some unity, something to start from, some common ground or specification on which to standardize insulation. This, of course, does not interdict a lower standard; it simply presupposes that an engineer wishes the best, and these are the means to insure it. If he wants Code wire, that is another question.

Mr. Fisher asks me about the 1 000 000 cir. mil cable, $\frac{13}{32}$-in. in. wall, in which he questions the possibility of 3 000 megohms per mile being lived up to. Now I would like to ask a question in return. Why did he not question the other insulation resistances; that is, the smaller sizes of copper? The insulation resistance does, under favorable conditions, indicate indubitably the character of the compound. It is impossible to go above 500 or 600 megohms with Code wire, whereas if you put 30 per cent. Para rubber in the compound, you will get 4, 5, and even 6 times what the Code wire will show. This proves two things; first of all, that chemical analysis is valuable if carried out properly; and secondly, that the insulation *does* indicate the character of the compound.

Wallace S. Clark: I dislike to go back on a fellow-laborer in the field, but there are one or two things in Mr. Langan's paper I do not agree with, and in fact do not think they are so. In the first place in referring to Code wire and the cheap material on it, he says, " It possesses no vitality, no dielectric strength, no capacity for work." A great many buildings in New York are strung with that wire and the wires are working satisfactorily.

It is altogether wrong to assume that rubber is the only possible insulating material. It is about the only elastic insulating material, to be sure, but there are lots of insulating mixtures containing little rubber which are perfectly good for ordinary low-voltage service.

He says that rubber is unrivalled for all purposes. I agree with Mr. Fisher that the statement is entirely too broad, and I think experience will bear that out. He also says that the percentage of resin and extractive matter in fine Para seldom exceeds 1 per cent. That was true 10 years ago, but it is not true to-day The quality of fine Para so far as the resinous matter is concerned, is deteriorating. It averages now 2 per cent. or more. His voltage tests are entirely wrong in this way; he does not test the cable nearly high enough. On a

3 500 working pressure he proposes to test with only 5 000 volts. A 250 000-cir. mils cable 3 500-volt class with $\frac{3}{32}$-in. insulation is to be tested at 5 000 volts. His 250 000 cir. mils low-tension cable with $\frac{6}{64}$-in. rubber, which seems to me the same as $\frac{3}{32}$-in., is only to be tested with 1 000 volts. The voltage test should be a factor of the size of the cable and the thickness of the insulation. Then the engineer can determine the factor of safety. If he wants to use a cable tested with four times, or twice the working pressure, he can do it. Then Mr. Langan speaks of getting a piece of insulation $\frac{1}{2}$-in. wide and $\frac{1}{16}$-in. thick. He might get that from some pretty good sized cables, but not from a No. 14 wire.

Another thing is the statement:

> It frequently happens that a cable may pass an exacting puncture test and be to all appearances in first class condition, when in reality the insulation has been so strained that it collapses at the first physical or potential strain imposed upon it.

The cables that were made for the Niagara Falls-Buffalo line, and whose record is in my paper, were all tested for an hour with 25 000 volts and they had $\frac{9}{32}$-in. of insulation. He recommends for such a cable 15 000 volts for one minute. He says that these cables were overstrained and that they were likely to break down in service, and would break down, and yet they have made a very good record. There are 60 000 ft. of cable in operation which contradicts that assertion. It is wrong to test a cable to the breaking point. But if a cable is tested as low as Mr. Langan recommends, there might be an indentation in the cable that would reduce the insulation at one point to two-thirds or even one-half normal thickness, without the test he proposes discovering that fault.

Exception has been taken to the statement regarding the difference in breakdown test on leaded cables and cables in water. It does not make any difference whether rubber cables are tested under water or leaded. I would rather test a cable under water, without lead, because it would be cooler under high potential.

Referring to Mr. Fisher's question, and also to the curves which Mr. Stott shows, I can endorse these curves as probably entirely right, because I have obtained similar results in many cases. I think that the compound in this case was made of a certain percentage of rubber and dry mineral matter, the composition of the dry mineral matter being the same in all cases; in other words, they did not make the very best compound they could with the 40, 30, or 25 per cent. of Para, but made them all on a common basis. That is the reason why the 17.5 per cent., with a lot of reclaimed rubber, shows better than the 30 per cent.

Referring to the specifications of the Rubber-Covered Wire Engineers' Association referred to in my paper, they are not intended to cover all the wire manufactured. I want to impress that idea as much as possible. They are simply intended to cover the point where an engineer wants an especially good class of rubber insulation for some special work, such as a central station job, or something of that kind, where the life of the cable is important and the conditions more or less severe. The reason that the 6 per cent. extractive matter is allowed is to allow the making of the best compound which the manufacturer is able to make with the 30 per cent. of Para. He can put in some other matter beside minerals. His extractive matter from Para will not run to more than 3%. The specifications take care of the fact that if the individual manufacturer is not trusted by the individual purchaser, the individual purchaser can go to the factory and satisfy himself that the 30 per cent. of Para goes in. The manufacturer can make the 70 per cent., the balance, of whatever he chooses, to get the best results.

Dugald C. Jackson (by letter): Referring to the results of the tests made by Mr. Stott, tests which indicate that the insulation resistance of rubber-covered wires varies with the test voltage I notice that this fact is denied by certain of the other participants in the discussion.

Several years ago I made observations similar to those which Mr. Stott sets forth; namely, that certain rubber-covered wires show a decrease in insulation resistance as the testing voltage is increased. I also found that some rubber-covered wires did not produce this phenomenon. At the time, it was impossible for me fully to investigate the conditions which caused the difference between the wires showing the effect and those not showing it, but it appeared that the wires of highest quality showed, as a rule, less change in insulation resistance with change of test-voltage, while wires of very poor quality showed the most change and, in some instances, a very large change. Even in the instances where the change was considerable, the same results could be obtained day after day; that is, my tests were completely reproducible. It appeared to me at the time that this might afford one way of arriving at the purity and value of the rubber insulating compound on different wires, and I discussed it with several gentlemen, as I then hoped to find leisure to continue the investigation further. I shall add that all of the manufacturers of rubber-covered wires with whom I then discussed the matter denied that such a phenomenon exists. My tests convinced me of its existence, however, as apparently Mr. Stott's tests have likewise convinced him. Unfortunately, leisure did not afford an opportunity for carrying on the work. It seems to me that this is a matter worthy of further investigation.

DISCUSSION AT MINNESOTA BRANCH, MAY 4, 1906.

F. R. Cutcheon: Mr. Langan objects to the puncture test for insulation on the supposition that the insulation may stand up well under test and deteriorate very rapidly thereafter. In cable work it is common practice to specify that the puncture test shall be repeated at stated intervals, usually covering a period of five years; I believe that this overcomes the objection, and with this provision the puncture test is the most reliable. Insulation resistance, in my experience, has proved of no value as an indication of the condition of a cable; this is especially true of multiple-conductor cables for high voltage, since the contact with the lead is very slight if it exists at all. The jute filling will serve to give a high-insulation test, but will break down when subjected to a high voltage.

In his specifications, Mr. Langan omits any reference to a standard of flexibility. Under this head would be specified the size and number of strands, the percentage of tin in the lead; and for paper or cambric cables the number and thickness of layers of insulating material. I have recently specified that a test piece of cable shall be capable of bending on a radius equal to five times the diameter of the cable, then bent in reverse direction, and after being straightened shall be capable of standing a puncture test with double the working voltage.

The degree to which a puncture test should exceed the working voltage depends upon the factor of safety allowed by the maker. There is a tendency to cut down the factor of safety in the higher potentials to avoid extreme bulkiness, hence it is inadvisable to use double the working voltage on such cables.

I see no reason why, for purposes of comparison, rubber cables should not be tested with the lead on, since this is the condition in which they are installed, and with which all later tests must be compared. When tested in this way, a rubber cable should stand the same puncture test as a paper cable.

J. H. Schumacher: I have looked up a great many grounds in conduit work on low-pressure wiring, carrying less than 500 volts, and have never found the ground to occur in the wire insulation. In most cases the trouble occurs in an imperfect joint. In my opinion the insulation furnished under present underwriters' specifications is ample for low voltages, even though it probably contains no rubber.

H. J. Gille: No consideration is given to anything but rubber cables in these papers. The St. Paul Gas Light Co. has had one rubber and one paper cable, each about three miles long, operating in parallel under 25 000 volts' pressure. The cables have been in use for five years and little difference has been noted in their serviceability.

John Pearson: When the rubber cable is in alone the power-factor at the power station, 25 miles distant, is about 1 per cent. higher than with the paper cable alone.

E. H. Scofield: The Twin City Rapid Transit Co. has a paper-insulated cable 10 miles long between Minneapolis and St. Paul which has operated for seven years at 12 000 volts and is still in service. Paper cable is used exclusively.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28, 1906.

ENGINEERING HONOR.

PRESIDENT'S ADDRESS.

BY SCHUYLER SKAATS WHEELER.

While I have prepared in writing something of an annual address, as required by the Constitution, I shall try to express the substance of my theme to you directly, because I attach some importance to the emphasis that can be given only in this way. All that I would say has been summarized by Francis Bacon in the preface to his " Maxims of the Law " where he says:

"I HOLD EVERY MAN A DEBTOR TO HIS PROFESSION; FROM THE WHICH AS MEN OF COURSE DO SEEK TO RECEIVE CONTENANCE AND PROFIT, SO OUGHT THEY OF DUTY TO ENDEAVOR THEMSELVES BY WAY OF AMENDS TO BE A HELP AND ORNAMENT THEREUNTO."

I feel that I cannot make a better use of the opportunity afforded me by this occasion to reach electrical engineers and the engineering profession, nor can I do our profession a greater service, than by raising my small voice in support of the principle so admirably stated by Lord Bacon. I will use my opportunity to urge that engineers interest themselves in improving the moral standard or the ethics of the profession and in strengthening their sense of the obligation that binds all engineers to a course that is particularly honorable.

We, as engineers, are accustomed to hearing ourselves referred to as professional men. The habit of calling us professional, though not strictly accurate, does no harm, and by encouraging us to greater care and conscientiousness ought to benefit. The relations between the clergyman, physician, or lawyer and his parishioner or client are regarded by law and usage as especially sacred and inviolable, and the obligation imposed upon the professional man to be faithful to the interests of the client or protege is equally strong. It is not in my mind to dwell upon these relations or even to attempt to describe them, because they are well known and established and the subject has been treated by many great authorities.

My wish is to draw the attention of engineers and others who are engaged for the people in handling the forces of nature and in interpreting its laws, to the propriety and necessity of regarding themselves as in the same category with the strictly professional man. The attitude of the public contributes to this obligation. The public considers (much more than there is reason for) that the several branches of engineering are special subjects and not easily within the comprehension of the layman, and therefore it places itself in the hands of the engineer. He is thus put under the utmost moral and professional obligation. The duty is as great as that of the physician to his patient, although engineers as yet do not generally recognize such responsibility.

On the other hand, the public finds no such declaration of high standards in the engineering profession as in the older professions. It is therefore inclined to treat the engineer lightly in ethics, and to withhold from him that deference which, if rendered, would in itself encourage a higher professional standard.

That much thought has already been given to the subject by engineers, architects, etc., is shown by the numerous discussions which have taken place in many of the societies. The conclusions reached by many of them, as expressed in the several codes of ethics formally adopted for the guidance of members, are very interesting and helpful. I ask " leave to print " at the close of these remarks, reference to these discussions and codes, with acknowledgement for the valuable assistance of my friend, Mr. Edwin Rust Douglas.

In a few cases, however, being prepared principally with a view to the relations of the members of the profession to each other, these codes are rather narrow and in the style of labor union rules. This suggests that greater weight be given in them to the interests of the client and the interests of the public.

The electrical branch of engineering, being the youngest, has not yet formally taken up the question of ethics, but should do so and will have the aid of the experience of all other branches of the profession.

The moral duties of the engineer may be summarized as follows:

First, the duty to the client. To see that his interests are protected, that he is wisely educated or advised as to what he ought to have. That he gets it. That information pertaining to him does not reach others.

Second, The duty to the public. To see that the public is not imposed upon by misinformation. The newspapers are full of descriptions of schemes which mislead the public and of wildcat stories that are a reflection on the engineering profession. Engineers are frequently called upon to discuss such schemes and to point out their absurdity; and are frequently unable to convince the layman that they are without merit, because the public mind is not sufficiently educated in engineering matters and because the professional standing of engineers in the community is not high enough.

Third, The duty to the engineering societies, which involves contributing to their welfare, both in time for administration and the preparation of technical contributions and discussions, and in money. There are three reasons for this obligation: first, the society represents the art or craft by which the engineer supports himself. Surely he owes it some debt; second, it is to his advantage that the branch to which he belongs should attain a position of strength and recognition, and that it should command respect for its opinions and endorsements; third, he should so conduct himself as to stand well in his society, whose members are his peers, and are therefore the men whose commendation the world will accept.

THE ENGINEER'S DUTY TO HIS CLIENT.

This is, of course, the most important obligation to be considered, and the one to which all others must give way if there is any conflict. This is the direction in which improvement in the attainment of loftier ideals, which may be expected from natural evolution as time goes on, will be most appreciated by the public, since in this direction the public is most affected. It is hardly necessary to say that the client is entitled to the very best there is in the engineer in thought and in service or execution, and I mention it only to make the statement complete. In drawing a comparison between our profession and the older or recognized ones with a view to selecting the lines along which we should try to guide our evolution and improve our standards, while I believe that the essential principles involved are the same, and that we should set our aim at as high and even a higher standard, there are some considerations which must not be neglected and which necessarily call for the employment of slightly different means in attaining the same end.

Many supposedly independent consulting engineers have affiliations with engineering or manufacturing concerns interested in the introduction and use of a particular apparatus. The engineer usually recommends the same apparatus, and its manufacturer recommends the engineer to clients. It is often held that the best engineers are subject to such affiliations, because the best are sought after and the absence of such affiliation is an indication of lack of capacity. This is not completely true, and there are many good men doing general work, though not nearly so large a proportion as of general practitioners in law or in medicine. The circumstance, however, imposes upon those who are subject to such relations the obligation to be especially careful when advising clients to acquaint the client fully with the fact of such relation and to divest themselves at the moment of any influence which might bias their judgment. Their advice will then have the increased value due to their special knowledge and experience.

Another fact which differentiates engineering from other classes of professional work is that study and work for a client takes the shape of drawings and data, which are usually regarded as the property of the engineer and not of the client. Such records are often voluminous, and are an exact statement of the affairs of the client as far as they go. Obviously, the custody of such matter involves important points in the relation of the engineer and the client, and if misused the consequences to the client may be serious. Even when an engineer is on the simple basis of an employee, it is sometimes suggested that sketches and data, such as may be contained in note books, are his personal property. In this connection, the fact that nearly the entire work of the engineer is reduced to and is represented by drawings and figures as stated, gives the subject great importance. Perhaps here is the greatest difference between the engineering and the other professions. There is no parallel in the so-called learned professions, and the client or patient, almost without exception, employs aid simply for experience and advice, and at no time does occasion arise for the reduction to a minute record of the preliminary or final results. In *this* respect moral responsibility devolves upon the engineer in greater degree than upon others. The point may well be illustrated in a more ordinary connection by considering the possibility of a manufacturer, founder, or artisan, furnishing to strangers articles made from designs, drawings, or patterns, the property of others which happen to be in his possession.

Professional relationship between the engineer and client in respect to its confidential nature and its inviolability is not thought to be like that of the physician or lawyer to client or patient, and is not so recognized by law. I believe the courts should so recognize it, and in any event the engineer should so regard it as applying to himself, and if anything should be even more scrupulous than the physician or lawyer. In these days most engineering is done for corporations, but while corporations are " artificial " persons, they are nevertheless created by the state and therefore the state has the right to dissolve them, to examine their books, to ask questions, etc., —rights which the state does not possess in the case of individuals. While this difference between the legal rights of corporations (which form the bulk of the clients of engineers) and the legal rights of individuals (who form all of the patients of doctors, all of the charges of clergymen, and many of the clients of lawyers), is not the cause of the difference in the legal status of the engineer's confidential advice compared with the advice of the physician or lawyer, it is yet suggestive of it and throws light upon it. Therefore, engineers should be the more careful in regard to matters of confidence.

To the engineer whose work is educational and whose clients are therefore his students, is given the opportunity to exercise at once the most direct influence for engineering honor, by his teaching. We may, therefore, expect that the profession will receive its greatest help from him.

THE ENGINEER'S DUTY TO THE PUBLIC.

Is largely educational or instructive. If the public believes that engineering is a subject it is not fitted by talent or training to deal with, whether it is justified or not in this belief, is not the engineer under the strongest obligation to guide it aright? When a man trusts you, you are bound to respect the trust, or you will lose your standing. We all know that a mass of misleading, foolish, and sometimes deliberately deceptive information on engineering or scientific subjects is given out, circulated, and published. All of this by its ultimate failure brings our occupation into disrepute. Many engineers, when asked, reply correctly, pointing out the misstatements and errors; but how many of us try to be good teachers? How many of us take care to see that the real facts, the real situation, the real need or the real possibilities are made plain to the layman? Take an ordinary case, such as the almost daily statement that someone has invented a new motor (not necessarily electric), so powerful that trains can be run a hundred or two hundred miles an hour by it. Assume that there are ten thousand engineers in the United States. I suppose that one thousand of these say each time the subject is brought to their attention, that it is absurd, that they don't believe it, that it has been tried two or three times but never successfully, etc. How many of even the thousand do you suppose take enough interest in setting the public right, to spend enough time to say that travel at any such speed is entirely a question of roadbed and right-of-way, that it is easy enough to make motors of almost any kind having power enough to pull a car or train at these speeds but that practical roadbed conditions prohibit it, and that the most perfect track ever built is so irregular that the train would be liable to jump the track at such a speed. Those who give true educational explanations in form digestible by the laymen, do their duty to the public, and do it and their profession a service. It ought to be clear to every engineer, and it probably is, that the more the public is enabled to understand the real facts, the more discriminating an audience it will become for the appreciation of really meritorious feats of engineering. At present I fear that in the public estimation, telegraphing to Mars is far ahead of getting the dry dock "Dewey" to Manila. When a man who is in a position to know, either as a result of training and education, or of Heaven-sent talents, is asked, by one who does not know, any question about engineering, physics, or the laws of nature, and he does not set that man right to the best of his ability, he is shirking his duty. Possibly he is assuming that he has a patent on some of the laws of nature, or a part interest. This view would not raise him in any ones estimation.

Another example occurs to me. I have seen a man as a witness in court, after qualifying as a patent expert, which means that he is officially clothed with authority as an engineer, and that he is there for the information of the court, spend hours and even days framing numerous answers to a single question, his sole object being to avoid, if possible, making a simple statement of the truth. The mistake, of course, is that the man confuses his duties and acts as an advocate, while the public understands that he is there as an engineer to make clear the facts. The result is well-known and gives rise to the saying, " Liars,—-liars and patent experts." The example serves my purpose well in illustrating by extremes what I mean when I say that it is the duty of an engineer to give the public the truest and simplest explanation of each engineering question when it comes up in his community, taking care to put it in such form as will be understood.

THE ENGINEER'S DUTY TO HIS PROFESSIONAL SOCIETY.

The other duties of the engineer I have placed before his duty to his professional society, because this latter relates to his solicitude for himself and his fellow engineers as distinguished from his solicitude for his client and for the public. The principle of doing something, however, for " your crowd " is so well established and recognized that it does not need full discussion here. I think even some animals act upon this principle. The institutions of crafts, societies, fraternities, guilds, and the like, is very old, and the reasons for them are sound and well known. Yet there are those who pay no attention to the official society representing the profession to which they belong. Rare and peculiar birds.

Unfortunately, some societies are at times not well run. The meetings are sometimes monotonous, owing to the presentation of matter which does not happen to relate particularly to or interest the members then present. The groups of men are not well balanced, some being older men with wide experience, while others are the beginners, and sometimes the meeting quarters are not comfortable. None of these things is an excuse. If the profession is young and poor, so are you. If you have prospered, you are a member of an important and successful profession, and then if the quarters are poor and the society not strong, it is your fault, because you have not contributed enough to make a society important in proportion to the position you have attained by work in the sphere of activity which it represents.

There are many ways in which you can support, encourage, and contribute to the dignity of your professional society, and you can select those means which are most agreeable to your own methods. Even the mere attitude of approval of the society is of great value. It is well to give your profession and the public to understand that you believe in your society and follow its recommendations and standards.

A more commonplace but none the less positive reason for your obligation to contribute to the support of your society, is that you are earning your living out of the art which it represents and which it is trying to dignify. Your obligation is therefore definite. It is also greatly to your interest that your profession be made as important and its position before the world as commanding as possible; and it would not be right were you to allow other professionals to bring about this result without your aid and then for you to reap any benefit from it.

In conclusion, I will mention what I believe to be the broadest and most important function of professional relations,—an engineer's standing or the way in which he is regarded by his contemporaries. All the world recognizes that the best judgment of a workman is by other workmen, of a woman by other women, of a lawyer by other lawyers; likewise the best estimate of an engineer as a man and engineer is by the members of his own profession.

APPENDIX.

PROFESSIONAL ETHICS.

References.

MINISTRY.—The ministry of each denomination has its code of ethics.

Usually found among the printed rules of church government.

LAW. "I have not been able to find a formulated code for lawyers, but have been told there is a well defined body of ethical rules which every attorney must conform to at the peril of being disbarred.

"In this country the series of lectures before the law class of the University of Pennsylvania in 1854 by Judge George Sharswood has become standard. It is not given as a formal code, but is a masterly treatment of the subject. No one can read it without a profound impression of the dignity, elevated standard of morality, devotion to the cause of truth and justice and the high sense of courtesy and loyalty to the profession with which the author deals with his subject." [From address of Mr. S. Whinery, Dec. 15, 1892, *Eng. News*, v. 29, p. 76.]

"It seems to be a fact that lawyers have no formulated code. Their rules of conduct are partly matters of tradition and partly interpretation and construction by various authoritative bodies, and form a valuable mass of professional ethics, but they have not been codified and adopted by the great Bar Associations in the United States." [From Report of Board of Direction of A.S.C.E., May, 1902.]

Abstract of article by Everett V. Abbott in the Harvard Law Review, Vol. 15, p. 714, 1901–2. Entitled "Some Actual Problems of Professional Ethics."

"The books on professional ethics with all deference be it said, deal somewhat inadequately with their theme. They do not solve the problems which, so far at least as my observation extends, most often present themselves for solution and the problems which they do discuss are treated with hardly sufficient care in analysis. The law schools usually ignore the subject and attorneys actively engaged in their profession follow such a diversity of theory and practice that in many matters of considerable moment and frequency there can hardly be said to be even a custom. The natural result of their conditions is that there is no well defined professional standard to which attorneys can resort in cases of doubt and therefore each attorney meets the questions which come to him—and they come to all—with only such light as an untrained instinct can supply. The need of a reasoned theory of a lawyer's duty illustrated and made vivid by actual experiences, seems to me, therefore, to be not the least of many needs of the time.

"The primeval fact * * * is that * * * the lawyer seldom if ever undertakes to bring about a definite result * * * *, but that * * * he does undertake to devote his best judgment to those matters which may be intrusted to him * * * his undertaking falls into that large class of contracts which import what is called a fiduciary obligation * * * Every fiduciary * * * should understand that when he allows his judgment to become impaired, he is not only committing a breach of contract, but he is committing a breach which involves * * * his personal honor as a man who may be trusted.

"The principal temptations which he meets * * * are legion and range from strong drink to adverse interests. * * * What are usually regarded as crimes of fraud, mainly consist not in deceit, but in the breach of fiduciary contracts through the surrender to adverse interests."

The author then considers at length the subject of rake-offs, rebates, preferential rates, etc., in their bearing on professional ethics, and goes on to say: "Out of all these considerations we may evolve a rule of thumb * * *. *If possible do not receive any compensation in your client's business, except from your client himself; but if circumstances compel you to break this rule, tell your client what you receive.*"

"The significance of that second clause perhaps needs explanation. The lawyer is often tempted to think that after all it is none of his client's business how much he has received. When that happens, he may be sure of three things: he may be sure, in the first place, that it is his client's business; he may be sure in the second place, that he is afraid to tell his client; and he may be sure in the third place, that he is engaged in the pleasing but futile process of self deception in trying to suppress a consciousness of unfaithfulness which will not be suppressed."

MEDICINE. "The Principles of Medical Ethics of the American Medical Association."

Adopted by the House of Delegates of the American Medical Association in May, 1903.

" Report of committee at annual meeting of House of Delegates, the governing body of American Medical Association, in New Orleans, the week previous to May 17, 1903.

" ' To the President and Members of the House of Delegates: Your committee has given extended and careful thought to the proposed revision of the Code of Medical Ethics referred to it for consideration. As you will note on caption of report, the word " code " has been eliminated and the expression " The Principles of Medical Ethics of the American Medical Association " adopted as adequately descriptive.

" ' In reference to this change it is proper to say that such action on its part is based on the idea that the American Medical Association may be conceived to occupy some such relation to the constituent State associations as the United States, through its Constitution, holds to the several States. The committee, for this reason, regards it as wiser to formulate the principles of medical ethics without definite reference to code or penalties, thus leaving the respective States, etc., to form such codes and establish such penalties as they may regard to be fitting and proper for regulating the professional conduct of their members; provided, of course, that in so doing there be no infringement of the established ethical principles of the association. The committee regards as wise and well intended to facilitate the business of the parent organization and promote its harmony this course, which leaves to the State Association large discretional powers concerning membership and other admittedly State affairs.'

" Your committee has retained to a large extent the phraseology of the existing code, while aiming at condensation of expression and a better understanding of some of its statements."

Signed.

ABSTRACT OF REPORT:

CHAPTER I.

DUTIES OF PHYSICIANS TO THEIR PATIENTS.

1. Physicians must be ever ready, mindful of their high character and responsibilities. Never forget the comfort, health, and lives of those intrusted to their care. Must unite tenderness, cheerfulness and firmness.
2. Must treat patients with attention and humanity. Must observe secrecy and delicacy.
3. The obligation of secrecy extends beyond the period of professional services. Private matters must never be divulged, except when absolutely required by the laws of the State.
4. Professional visits must be sufficiently frequent, and regular, though not too frequent.
5. Must not be forward to make gloomy prognostications, but should not fail to give timely notice of danger, often through another person of good judgment.
6. Physician should be a minister of hope and comfort.
7. Must never abandon a patient because deemed incurable.
8. Promote and strengthen the good resolutions of the patient.

CHAPTER II.

DUTIES OF PHYSICIANS TO EACH OTHER AND TO PROFESSION AT LARGE.

Article 1.—Duties for support of professional character.

1. Every one entering the profession incurs obligations to uphold its dignity and honor. It is incompatible to designate ones practice as based on an exclusive dogma or sectarian system.

2. Observe laws for government of members of the profession. Honor the fraternity, promote the science and art, and entertain due respect for seniors.

3. Each one should identify himself with the organized body in the community where he lives.

4. Local societies should affiliate with State and State with National.

5. Purity of character and moral excellence are required.

6. Be temperate in all things, prepared for emergencies.

7. It is incompatible to resort to public advertisements or private cards inviting attention of persons afflicted with particular diseases; to promise radical cures; publish cases in daily prints or suggest them to be made; to invite laymen to operations; to boast of cures; to adduce certificates of skill; or to employ any other methods of charlatans.

8. It is derogatory to professional character to hold patients for instruments or medicines; accept rebates; assist unqualified persons to evade legal restrictions; to dispense or promote secret medicines; or to give certificates attesting efficacy of secret medicines.

Article 2.—Professional services of physicians to each other.

1 Physicians should not undertake treatment of themselves or family. Professional aid is always gratuitously offered.

2. All physicians' families are entitled to gratuitous services of other physicians near them.

3. When summoned from a distance to attend a colleague, pay for expenses and loss of business should be offered.

4. When more than one physician attends another, one takes charge of the case.

5. It is sometimes necessary for a physician to withdraw from professional labor and appoint a colleague to act for a specified time. Compliance is an act of courtesy. It should be performed with consideration for the interest and character of the family physician.

Article 3.—Duties of physicians in regard to consultation.

1. Broadest dictates of humanity should be obeyed.

2. Consultations should be promoted in difficult cases.

3. Utmost punctuality should be observed.

4. The physician who arrives first should wait a reasonable time. after which the consultation is to be postponed.

5. No insincerity, rivalry, or envy should be indulged.

6. No statement or discussion should be made before the patient or friends, except in presence of all the physicians.

7. No decisions should restrain the attending physician from making subsequent changes in treatment as required by unexpected changes. But the reasons should be explained at the next conference.

8. The attending physician may prescribe for the patient; not so the consultant, except in emergency.

9. All discussions are confidential.

10. If two cannot agree, they should call a third. The consultant should not take charge of a case even on request of patient or friends, except in the rarest of cases.

11. Physicians in consultation should observe regard for the character of the attending physicians.

Article 4.—Duties of physicians in cases of interference.

1. Physicians should found expectations of practice on character and extent of education.

2. Physicians in intercourse with patient observe caution and reserve.

3. The same should be observed when visiting a person under the care of another physician. Such visits should be avoided.

4. Do not take charge of a patient recently under the care of another physician in the same illness, except in an emergency.

5. Do not make damaging insinuations about previous treatment by another physician.

6. When called in an urgent case, because family physician is not at hand, relinquish case on his arrival.

7. In sudden cases, if several physicians are summoned, the first to arrive should take charge, but he should request call of family physician, to whom the case is to be relinquished upon his arrival.

8, 9, 10. In certain emergency cases, the first physician arriving receives the fee.

Article 5.—Differences between physicians.

1. Differences should be referred to a sufficient number of impartial physicians.

2. A peculiar reserve should be observed toward the public in regard to professional questions and differences, neither the subject matter nor the adjudication of the arbitrators being made public.

Article 6.—Compensation.

1. Gratuitous services are rendered in some cases.

2. Gives class of services always to be charged for.

3. Local rules for minimum charges should be adopted.

4. Pay no commission and accept none for recommendations for treatment, etc.

CHAPTER III.

DUTIES OF THE PROFESSION TO THE PUBLIC.

1. Be vigilant for welfare of community, as good citizens, ready to give counsel to the public.

2. Enlighten the public regarding quarantine regulations, hospitals, asylums, etc., measures in contagious diseases, etc., and in pestilence face the danger.

3. Enlighten inquests and courts when called by the authorities. Compensation is just.

4. Make known wrongs committed by charlatans.

5. Promote profession of pharmacy.

The Medical Society of the State of New York voted to abandon its code of ethics. Its president states, " It would mean more to the character of the medical profession and would enhance the respect in which it is held by the general public, if the specific rules of ethical conduct were obliterated from the By-Laws of the State Medical Society, and if the regulation of such matters were hereafter left to the judgment of individual practitioners influenced by professional opinion and by local custom."

ARCHITECTURE. Code of Ethics of the Boston Society of Architecture.

1. No member should enter into partnership in any form or degree with any builder, contractor, or manufacturer.

2. A member having any ownership in any building material, device or invention, proposed to be used on work for which he is architect, should inform his employer of the fact of such ownership.

3. No member should be a party to a building contract, except as "owner."

4. No member should guarantee an estimate or contract by personal bond.

5. It is unprofessional to offer drawings or other services "on approval" and without adequate pecuniary compensation.

6. It is unprofessional to advertise in any other way than by a notice giving name, address, profession, and office hours, and special branch (if such) of practice.

7. It is unprofessional to make alterations of a building designed by another architect, within ten years of its completion, without ascertaining that the owner refuses to employ the original designer, or in the event of the property having changed hands, without due notice to the said designer.

8. It is unprofessional to attempt to supplant an architect after definite steps have been taken toward his employment.

9. It is unprofessional for a member to criticise in the public prints the professional conduct or work of another architect, except over his own name or under the authority of a professional journal.

10. It is unprofessional to furnish designs in competition for private work or for public work, unless for proper compensation, and unless a competent professional adviser is employed to draw up the "conditions" and assist in the award.

11. No member should submit drawings except as an original contributor in any duly instituted competition, or attempt to secure any work for which such a competition remains undecided.

12. The American Institute of Architects "schedule of charges" represents minimum rates for full, faithful and competent service. It is the duty of every architect to charge higher rates whenever the demand for his services will justify the increase, rather than accept work which he cannot give proper personal attention to.

13. No member should compete in amount of commission, or offer to work for less than another, in order to secure work.

14. It is unprofessional to enter into competition with or to consult with an architect who has been dishonorably expelled from the Institute or Society.

15. The assumption of the title of "architect" should be held to mean that the bearer has the professional knowledge and natural ability

needed for the proper invention, illustration, and supervision of all building operations, which he may undertake.

16. A member should so conduct his practice as to forward the cause of professional education and render all possible help to juniors, draftsmen, and students.

ENGINEERING.

1871. August. R. P. Rothwell. " Professional Morality." Paper presented at the Bethlehem meeting of the American Institute of Mining Engineers.

Not found in Transactions. Printed in an early volume of the Engineering and Mining Journal.

1886. February. J. C. Bayles, " Professional Ethics."

Presidential address American Institute Mining Engineers, Transactions, vol. 14, p. 609.

Abstracted:

" * * * He does not need to be reminded that he cannot sell his independence nor make merchandise of his good name. But, as delicate problems in casuistry may mislead or confuse him, it is to be regretted that so little effort has been made to formulate a code of professional ethics which would help to right decisions those who cannot reach them unaided. * * *

" An ever present stumbling block * * * is * * * 'the customary commission' * * * Why do manufacturers pay commissions? Is it probable * * * they give something for nothing? Is it not certain * * * they are seeking * * * to warp his judgment and make him their agent?

" Gentlemen, it is not true that custom sanctions the acceptance of commissions by engineers. It is incompatible with a standard of professional honor to which every engineer should seek to conform. * * *

" * * * I characterize as unprofessional the framing of specifications calling for patented or controlled specialties, when to deceive the client, bids are invited. * * * There is nothing unprofessional in recommending a patented article * * * but he will do it openly. * * *

" In the relation of engineers to contractors there is many a pitfall * * *. Frequently the engineer has all he can do to hold the contractor to a faithful performance * * *. It often happens that the engineer, defeated and discouraged, gives up in the unequal battle. From that moment he is of no further use as an engineer, and if he remains for an hour in responsible charge of work he cannot control, he rates his fee as more desirable than a reputation unsullied * * *.

" In making reports for contingent fees * * * the young engineer needs to exercise great discretion * * * takes a fearful risk, however honest he may be * * *. Contingent fees are a delusion and a snare and in making it a rule to refuse them, the young engineer will be likely to gain more than he loses.

" Reports * * * upon subjects concerning which the engineer knows himself unqualified * * * are * * * charlatanry.

" Of a professional reputation dependent upon the accuracy as well as the honesty of reports *ordered* and *used* for *speculative purposes*, one may say, as a marine underwriter said, * * * 'he wouldn't insure her against sinking between Castle Garden and Sandy Hook with a cargo of shavings.'

" In the matter of expert service in the courts * * * the conscientious engineer has no right to appear as a partisan of anything except * * * the truth.

" How far an engineer can properly use for his own advantage information gained in the discharge of duties of a confidential nature, is a question at once delicate and difficult. He cannot help knowing * * * and his knowledge is his capital * * *.

" The manager who advises his brokers by telegraph and his principals by mail, cannot * * * have * * * delicate sense of right and wrong.

" In professional criticism of professional work it is easy to fall into ways which are wrong * * *. I regard as unprofessional every effort to discredit honest and intelligent work, and every form of disguised advertising * * *.

" There are certain broad ethical principles * * *. One is that a man cannot serve two masters * * *. Another is, that * * * if the *intent* to deceive is there, he lies.

" Professional ethics are no different from the ethics of the decalogue. But * * * I do not know that any engineer can make for himself a creditable and satisfactory career, of whom it cannot be said that * * * he has held his professional honor above suspicion."

1886. May. M. F. Durfee, " Ethics of Engineering." In discussion of paper " The Training of a Dynamic Engineer ". Read before A.S.M.E. Points considered:

1. Duty of Assistant to Chief.
2. Relations and Duties of Engineers to each other.
3. Duty to Employer.
4. Duty of Profession to Society at large.
    a. Be loyal.
    b. Do as you would be done by.
    c. Be honest and zealous.
    d. Secure confidence of public.
    e. Protect society from pretenders.

1891–1892. Austin Dam Case.

In the Austin Dam Case a code of engineering ethics would have been of great value. This relates to the building of the large storage dam and reservoir at Austin, Texas. The engineer appointed on the job was continually over-ridden by the mayor of the city. His designs were changed and his work interfered with. Without consulting him, another engineer was engaged to report on the work and this second engineer was finally put in charge of the work over his head.

This seems to have made quite a stir among the civil engineers fourteen years ago.

1892, November 10. Engineering News Editorial.

" In every professional act the consulting engineer owes a duty to three persons: 1st, to himself and to his own reputation; 2d, to his client or employer, to give him the full benefit of all the knowledge and judgment he has; 3d, to his fellow engineers, and especially to any engineer directly affected by his acts."

Editorial states that a code of ethics is a matter of slow growth, a gradual general acceptance of rules of conduct that have been more or less traditional and that " the only aim of such a code is to establish equity and courtesy between the different members of the same profession, and whoever distinctly violates equity and courtesy in his treatment of a fellow engineer, violates—if not an already established code, as we believe he does—at least what will be the code when there is one, and what every engineer should seek to establish."

This editorial defines two principles of a code of ethics as follows:

" 1. It should be considered unprofessional and dishonorable for any engineer to accept a call in consultation for any work, which is already in charge of an engineer, *except the call come from or through such engineer in charge.* Engagements tendered from principals should be considered as accepted *only* when there is no engineer already in charge of the work.

" 2. It should be considered unprofessional and dishonorable for any engineer to report upon such work which is already in charge of an engineer, *except to such engineer in charge.* Reports to principals direct should only be made when there is no engineer in charge; nor then, when there has been an engineer in charge whose professional acts are impeached in such report, without prior tender of a copy of such parts of the report as may personally concern him, for his perusal and response."

1892. December. J. B. Johnson, " The Birth of a Profession."

Presidential address, Engineers' Club, St. Louis. Journal of the Association of Engineering Societies, Vol. 12, p. 78.

Abstract:

" In short, I would say that a vocation only becomes a profession when an acceptable performance of its duties demands the continuous exercise of scholarly attainments * * *.

" In analyzing the status of the engineering profession in America, therefore, I conceive that we may divide the embarrassments under which we labor into two classes; those conditions outside our ranks and those inside. The most embarrassing external conditions are:

" 1. The universal confusion on the part of the general public as between a surveyor * * * or * * * a mechanic * * * or a superintendent * * * and an * * * engineer.

" 2. The confidence that all our capitalists have in their own judgment on all kinds of engineering questions * * *.

" The chief embarrassments from within * * * are * * *

" 1. Too low an idea of professional accomplishments * * *.

" 2. The failure heretofore to give due weight to both theory and practice * * *.

" From this showing * * * it is evident that the engineering profession in America is in a state of rapid development * * *.

" Out of this there soon must grow a high standard of professional etiquette and ethics * * * and with these will come that recognition from the community * * * which every man * * * hopes to attain * * *."

1892. December. S. Whinery, " Ethics of Civil Engineering."

Address Cincinnati Engineers' Club. Engineering News, January 26, 1893.

Abstract:

In the earlier days of every craft or profession, the feeling between individuals is jealousy and rivalry. In time this gives way to tolerance, then to meeting for protection of common interests and so to mutual respect and professional brotherhood.

Careful regard for rights and privileges of others, and decision of questions as they arise, causes accumulation of set of rules.

These rules may properly be termed "Professional Ethics."

Older professions have such codes, *whether reduced to writing or not.*

Engineering a new profession, recently crystalized from occupations and crafts. This short life cause of absence of code. Time is required to develop the necessity for it, and experience to determine what rules should govern.

A correct code of ethics must be founded on the decalogue and along lines of universal system of morals.

Following the code of medical ethics, it is convenient to divide the subject into heads.

1. Duty of engineer to his profession.
2. Relation to his professional brethren.
3. Duty to his clients or employers.
4. Duty to public.
5. Duty to himself.

Quotes from code of medical ethics applying it almost literally.

1. Every engineer owes it as first duty to be, to say the least, above suspicion. Owes it to add to professional store of knowledge; should esteem it a duty to make public new data and experience.

A prevalent feeling exists against "rushing into print." But in this matter a golden mean exists.

Engineers should not only conform to strict morality but avoid minor offences against proprieties, as advertising by more than professional card, by boasting, etc., but may give professional titles and degrees and names of scientific societies.

Should found expectations of practice on qualifications, not on intrigue or artifice.

In medical profession it is considered unprofessional to hold a patent. Some prominent civil engineers have taken the same position. Perhaps engineers should contribute such inventions as relate to improvements, whose value is confined to members of the profession, but it is not clear why the public at large is entitled to free use.

Unprofessional to accept commissions, presents from contractors, etc.

Should not undertake engagements they are not competent to fulfil with honor.

Unprofessional to speak disparagingly of fellow engineers, indulge in rivalries, express hasty opinions, volunteer advice where not solicited, to criticise adversely in public.

2. Who are his professional brethren? No formal standards, as in law or medicine, exist.

Professional courtesy is claimed by every quack. Where shall the line be drawn? Each must judge for himself. No difficulty in case of great majority.

When a case of unmistakable charlatanry is met, it should be exposed.

Must refuse to consult with quacks, but must discriminate between mere lack of judgment or experience and the violation of known principles.

Want of respect shown by the public is due to the same between members; therefore duty is to show highest respect and courtesy.

Consultations between engineers should be subject to rules of etiquette as in the medical profession.

3. Two classes of engagements—on salary, under direction of another engineer,—on fees reporting to officers of corporations.

Duty is to devote himself to interest of clients. Personal affairs must not stand in the way. Only exception is when demands or interests of client conflict with sense of right and wrong. Even this is not allowed in law; but it is impossible to take that stand in engineering. Must give the truth, the whole truth, and nothing but the truth in reports on property, etc.

After a professional engagement may an engineer accept another engagement that may be inimical to former client? No principle in law is more firmly established than that a lawyer may accept cases where he may oppose former client, but *must not make use of confidential information* obtained in former connections.

To what extent do facts and results acquired belong to client, and to what to engineer?

All original notes, maps, plans, etc., and final result and report belong to client who pays for the work, but engineer may retain copies as part of his stock of knowledge; but it is not honorable to use such facts to oppose business of former client.

No understanding as to proper minimum fees. Doctors and architects have one. Need for concerted action. Should be agreement in any locality.

Should not openly solicit preference and bid against each other. Humiliating in extreme.

In no other profession are members so inadequately paid; due to competing and bidding against each other. Special knowledge should commend special compensation.

Assistants should be loyal and faithful, carry out instructions and report on progress to chief, and treat information as confidential. Avoid adverse criticism of superiors to outsiders.

4. Owes to public best services as a citizen. Quote Code of Medical Ethics.

5. Owes it to himself to make best of abilities and opportunities, to defend professional character and rights.

Should not be a tool of unscrupulous men nor be saddled with their blunders or misdeeds.

Should not neglect personal business interests. Seek honest competency.

No adequate foundation for delicacy about taking advantage of business opportunities met. May engage in any honorable enterprise, that does not interfere with interests of employer, will not *influence professional action in reference to employer* or occupy employer's time.

Should be more than an engineer, needs every kind of knowledge and culture that can be obtained.

1893. March. Boston Society of Civil Engineers. "The Relation of the Engineer to those with whom he comes in professional contact."

Journal of the Association of Engineering Societies, vol. 12, p. 437.

Several short papers on the following subjects:

"The Relation of the Engineer to his Brother Engineer." Compares medical code. Mentions strife to secure work, jealousy of others' success. Ungentlemanly treatment of subordinates.

"The Relation of the Engineer to the Public." Considers necessity of high public standing.

"Relation of the Engineer to the Public and to the Press." Engineer should be a leader of public opinion.

"Engineer in Relation to his Clients." Claims position of engineer is not what it ought to be. Engineering Societies should take action regarding public matters.

"Relation of Engineer to his Assistants or Subordinates." Helpfulness to assistants and subordinates. Personal interest. Bring them in closer contact with mind of chief. Give full credit for work.

"Engineer as an Expert Witness." Profession often brought in disrepute by two engineers controverting each other's testimony. Engineer should not sell his reputation for a fee.

"Influence of his Profession upon the Social Relations of the Engineer." Engineer must be honest, helpful, etc.

1893. June.

A resolution was presented to the A.S.C.E. for the appointment of a committee, "to collect information and to consider the propriety of the adoption by the Society of a code of ethics for the profession and to make such other recommendation as the committee thinks proper."

1895. October. J. Vander Hout, "Field-notes of a Civil Engineer. Do they belong to his client or to himself?"

Address Engineers' Society Western New York. Journal Association Engineering Societies, vol. 23, p. 32.

Abstract:

Divides into classes.

1. Engineer paid for all he does.
2. Engineer paid only for *result* of work.

First-class.

1-a Engineer receives a salary.

1-b Engineer has a general practice and charges for his time.

In either 1-a or 1-b, decided that all his work, notes, and results of his work belong to employer or client, and engineer has no legal right to make copies for his own use without permission. Custom, however, permits him to make copies, but he should not later use either these copies, or any knowledge gained, to detriment of former client.

In second class, where an engineer is doing piece work, original notes certainly belong to engineer, but his work cannot be considered complete unless, from the report he makes, another engineer could duplicate his results or relocate his work. Unless his report is detailed, copies of all notes, etc., should therefore be delivered to client.

1896. January. J. S. Keerl, "The Standing of Engineering among the Professions."

Address Montana Society of Civil Engineers. Journal of the Association of Engineering Societies, vol. 16, p. 71.

Abstract:

"There is another calling, a profession not nearly so old, in fact an infant in view of the antiquity which surrounds the history of those above mentioned (law and medicine) * * * a profession which many savants have pronounced the only one which does not live by the contentions, miseries and distresses of humanity * * * the engineering profession * * *.

"While, as engineers, we have no fear of the results from a comparison of our achievements with those of other professions, yet, as one who has served something like twenty years in the varied branches of engineering, I would ask whether we have secured from the public that full recognition and emolument, which the importance of our profession would seem to justly demand * * *.

"From my standpoint, I fail to see any reason why the engineers of our day * * * should not be fully recognized in public affairs, and especially upon those Government and State Commissions where their special training and knowledge would be of great service to the public."

1896. February. "Code of Engineering Ethics," adopted by the Canadian Society of Civil Engineers.

Duty of the Engineer to his client.

1. Every member of the Society should perform the work he undertakes to do to the best of his ability and in the true spirit of his engagement, feeling it to be his duty to present all ascertained facts in their true light.

The Client's Obligation to the Adviser.

2. The Civil Engineer has a right to expect from his client the same consideration and deference to his opinion, as is by their clients accorded to the members of other professions,—law and medicine for example—and without which the adviser should decline to advise. The surest way for the engineer to obtain such necessary consideration and deference from the public, will be found in his manner of carrying himself.

Mutual Relations of Chief and Assistant.

3. The assistant engineer must loyally obey and support his chief, to whom it will be his duty to report directly on all matters relating to the work on which they may be jointly engaged. His report should be full and explicit on all important points and exact as to the best of the assistant's knowledge and belief, cloaking nothing, even though going to show that previous reports had been inaccurate or not duly weighed in some particulars affecting the well-being of the business in hand.

4. The assistant engineer is entitled to look to his chief for and to receive from him advice for his guidance in the proper performance of his duties and, where right, to expect his support in matters of dispute between him (the assistant) and his subordinates or between him and the contractors working under him. He is also entitled to the aid of the chief engineer's professional experience or counsel where unlooked for or extraordinary difficulties present themselves or changes of original

plan may be called for in the work on which they are associated, so that responsibility may be fairly apportioned between them.

5. It is the duty of both chief and assistant, each in his department, to study economy in the doing of the work, the management of which they have undertaken, and in every way consistent with the maintenance of the good character of the work to make the client's interest the guiding object.

6. The engineer may legitimately suggest experiments with a view to improvement, whether in methods of doing the work which he oversees, or for raising its character, but such experiments should only be undertaken with the full consent of the party, whether client or contractor, on whom the expense may fall, and on the understanding that to them will occur all pecuniary benefit from the success of the experiment.

7. It shall be considered unprofessional for any member of this Society to seek the position of an expert to report on any work that is in charge of a recognized engineer.

8. It shall be the duty of any engineers before examining any work with a view to report thereon, to give the engineer due notice before going on with the investigation, in order that he may have every facility to explain and sustain his methods of carrying on the work in question.

Professional Services of Engineers to each other.

9. Interchange of professional assistance between members, as tending to promote fraternal intercourse and mutual good will, is not to be discouraged, but neither is it to be considered obligatory on a member to respond to the request of a fellow member for professional counsel or assistance. Service so rendered must be entirely voluntary on the part of the member whose aid is sought.

Pecuniary Matters, Advertising, etc.

10. The Civil Engineer may consistently with professional status take out patents for new inventions or for improvements on old ones and may sell or otherwise dispose of the patents for his own advantage. He may undertake the survey and the engineering of works by contract or he may contract for the construction of works on a percentage of their cost. Advertising with a view to attracting business should, where resorted to, be as far as possible free from egotistic or self laudatory references and expressed in language not derogatory to the dignity of the profession.

Duties of the Civil Engineer to the Public.

11. The Civil Engineer whose advice is sought in respect to the usefulness, practicability and cost of a work should, before expressing his opinion, obtain reliable information on all points involved in the matter submitted to his judgment, including the probable paying capacity of the contemplated undertaking. He must be cautious how he recommends large preliminary outlay, should avoid connecting himself with schemes or projects of merely speculative character, always bearing in mind that his professional reputation will be to a great extent judged by the inherent worth and commercial value of the undertaking with which his name may come to be associated.

1901. September. James Owen, " Is it Unprofessional for an Engineer to be a Patentee? "

Discussion on another paper Transactions A.S.C.E., p. 479.

In Mr. Owen's opinion it is entirely unprofessional for a Civil Engineer to get any patent on any work which he has constructed.

1901. December. A.S.C.E. Topical Discussion.

" Do the interests of the profession, and the duty of its members to the public, require that only those who are competent be allowed to practice as civil engineers?

" Under what authority, through what agency, and upon what evidence of competency, should applicants be admitted to the practice of Civil Engineering? "

Quotations from discussion:

" In this country the great profession of Engineering in its several branches, is alone in being open to the pretender and the quack."

" From the nature of our Government it is impossible to secure national action in the matter, and the several State Legislatures alone must be looked to for the necessary legislation."

Enactments in the several States should be as nearly uniform as possible.

Suggests 1st—Defining term " Civil Engineer."
2d—State Board of Examiners.
3d—Licenses of three classes.
1st class—Long experience and marked ability.
2d class—Intermediate.
3d class—Technical graduates, little experience.
4th—No one practice without a license.

Law should not apply to Engineer Corps of U. S. Army or to Civil Engineers of U. S. Navy, when on government work.

5th—Board revoke licenses for good cause or degrade in class.

Opposes having A.S.C.E. represented in any way.

Others disapproved State action. All approved that incompetent persons should in some way be disbarred, or that the State merely certify, not license. National Government could do this also.

1902. April. A. R. Eldridge, " Is it Unprofessional for an Engineer to be a Patentee? "

Paper, A.S.C.E. Transactions, vol. 48, p. 314.

S. Whinery in discussion says in abstract no valid reason can exist for denying engineer right to patent inventions that have no connection with his profession. * * * Public at large has no legal or moral claim because of his vocation * * * Duty as citizen is discharged when he pays his taxes. * * * Inventions are personal property of the inventor.

What claim has profession on inventions of members? No legal right or moral right? But it * * * has claims not less real because somewhat difficult to define. Embraced in general term, " Professional Ethics." May assume products of engineers' brain are as much his personal property as products of his hands * * *.

Inventions relating to profession may be divided into two classes: 1st, those relating to engineer's workshop, instruments, etc. Open question whether use should not be free to all. In medical profession it is distinctly improper to patent these. 2d class, inventions that confer no special benefit on profession. He is entitled to patent these and receive compensation.

Impression that in medical profession it is unprofessional to take out a patent of any kind. Not so. Only patents on instruments and medicines are barred.

What claim has client on engineer's inventions? 1st case: Where invention is made in client's employ, legal status will settle. " A " takes out patent in " B's " employ. " B " entitled to free use in his business, but no other claim on it. " A " may sell it to any other persons in whole or part. 2d case: Where engineer made invention before entering employ of client. Should not use it, royalty or no royalty, without permission of client.

The writer believes that the time has come when the profession should take a positive and unmistakable action on this question of the right of the engineer, not only to invent, but to protect his invention in the way the law has provided.

1902. May. Report of Board of Direction A.S.C.E.

The resolution of June 1893 for appointment of a committee, " To collect information and to consider the propriety of the adoption by the Society of a code of ethics for the profession and to make such other recommendation as the committee thinks proper."

Transactions A.S.C.E., vol. 49, p. 45.

Abstract of Report of Committee:

Arguments in favor.

1. The resolution is for appointment of special committee, etc. Does not commit the Society. There should be no objection to the appointment of such committee to consider the question.

2. The evident difference of opinion among engineers as to the necessity for a code of ethics, is a good reason why committee should be appointed to consider the matter.

3. There is some question as to whether civil engineering may properly be called a profession. The Century Dictionary's definition of " profession " is quoted. This definition seems very clearly to apply to the actual facts of the practice of civil engineering.

4. Rules do exist which govern relations to each other and to the public, of men following other professions, not only to the " old professions," but to such vocations as dealing in stocks and produce.

5. Will not the character of civil engineering and the relations of members to themselves and to the public be improved by a code of ethics?

4. It seems to be a fact that civil engineers do in some instances permit themselves to act in ways which in other professions would be considered unprofessional and improper.

7. Lack of rules affords excuses for such conduct.

8. The fact that many engineers are in salaried positions should be an argument for appointment of such a committee. Those who require the services of an engineer are apt to base their estimate on the standing which the engineer himself takes.

Arguments against.

1. It may just as well be asserted that the other great professions are great in spite of codes, not because of them.

2. It seems to be a fact that lawyers have no formulated code. Their rules of conduct are partly matters of tradition and partly interpretation and construction by various authoritative bodies, but not codified and adopted by the great Bar Associations of the United States.

3. The Medical Society of the State of New York has voted to abandon its code of ethics. Its president states, " It would mean more to the character of the medical profession and would enhance the respect in which it is held by the general public, if the specific rules of ethical conduct were obliterated from the By-Laws of the State Medical Society, and if the regulation of such matters were hereafter left to the judgment of individual practitioners influenced by professional opinion and by local custom.

4. It is believed that architects are also without a formulated and accepted code.

5. Rules governing stock and produce exchanges are not analogous. It is impossible to frame a code to cover all cases. It would be too complicated and minute to administer. It must therefore be a statement of general principles, but these have been made by moral teachers since society began.

6. A strict code would restrain those who need no restraint and would not be a guide to the unprincipled.

7. An engineer may be deterred by timid adherence to the code from doing his real duty to his client or himself.

A long discussion followed this report.

In this discussion the following points came up:

1. To what extent and in what ways may an engineer advertise his services?

2. Under what circumstances is he to own and control patents consistent with strictly professional practice?

3. What general practice should govern the condition of consulting engineers toward other engineers engaged upon work?

4. Under what circumstances should an engineer pass judgment on the work of his professional brethren?

5. To what extent should the circumstances of an engineer's private life be allowed to interfere with his professional standing?

6. Is it practicable or advisable that the Society should attempt to expose quacks?

7. What acts, if any, should make an engineer liable to the censure of the Society?

The motion to adopt the resolution, being put to vote, was lost.

1902. August. Robert Moore, " The Engineers of the Twentieth Century."

A.S.C.E. Transactions, vol. 48 (closing paragraphs).

" And it is, I think, safe to say that for the kindling of professional enthusiasm, and the establishment of high professional standards, the Society and its members will continue to rely, as they have done in the past, upon these vital and moral forces, and not upon the enactment of codes or upon any form of legislation.

" Indeed, anything which savers of compulsion is to be deprecated as not comporting with the dignity of a body of men chosen, like our own, upon a basis of education and approved character. We may safely trust such men to the guidance of their own sense of fitness and right and to the contagion of noble example.

" Moreover, any code that can be framed is certain to be antiquated to-morrow.

" As expressions of individual opinion and suggestions for the guidance of others, such rules may be of great value, but as official codes to compel compliance and take the place of individual conscience, they will be harmful rather than helpful.

" But, animated by the inspiration of example, personal contact, and friendship, hardly any limit can be set to the effect of our Society in lifting our profession to the highest plane of real service and honors well deserved."

1905. August. F. C. Osborne, " Engineering Ethics and Fees."

Paper read before Engineers' Club of Cleveland. Journal of the Association of Engineering Societies, vol. 35, No. 2.

Abstract:

Question of fees for engineers has not received the attention it deserves.

A complete schedule hard to arrive at; but for certain classes of work a fee based on a percentage of the cost of the construction seems practicable and equitable. The architects have had for years such a system, and it has grown to be recognized by the public and the courts. A few engineers have adopted the architects' schedule, and if more of them would do so, the result would be of advantage to all concerned.

When a large proportion of complicated mechanical work is involved, the usual amount of the fee, viz., 5%, is hardly sufficient. In fact in many cases a fee of 10% is not too much to cover complete plans, specifications and superintendence.

DISCUSSION ON " ENGINEERING HONOR," AT MILWAUKEE, WIS., MAY 30, 1906.

C. P. Steinmetz: The day before yesterday we listened to a very interesting dissertation by our worthy President on engineering ethics. I have in the last few days thought over this matter considerably. There is a code of ethics in all other professions. The high standing of the medical profession and of the profession of law is, in my mind, undoubtedly due to their strict code of ethics. Other branches of engineering also have some more or less universally recognized code of ethics. Our profession is the youngest one. There are still amongst us some of the early pioneers, who have seen the beginning of electrical engineering, and they are not so very old yet, either; even in our worthy Secretary we have one—and he is not so old, because as he tells me he is still riding a bicycle—men whose activity began during the times when electrical engineering consisted of telegraphy and nothing else.

While our profession is the youngest, it is one of the most important. Our national organization is the second largest engineering organization in the United States. However, problems have appeared which have to be met by the electrical engineering profession, problems of ethics which are different, to a considerable extent, to those met in other engineering professions. I want to draw your attention to a feature introduced by the fact that a very large percentage of the prominent electrical engineers are more or less closely associated with large manufacturing or large operating companies. Our organization is powerful, is of a very high standing; it is up to us, and it is within our power either to increase the standing of the electrical engineering profession, to put a ban on everything we consider improper, to raise the code of ethics of the electrical engineering profession, or to let matters slide and trust to Providence whether our standing shall rise or otherwise. I believe we should not do that. I believe we should consider the question of establishing ethics for the profession of electrical engineering; and I shall therefore make a motion as follows:

THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, in annual convention assembled, requests the President and the Board of Directors to nominate a committee to consider the advisability of drawing up a code of ethics for the electrical engineering profession, and if this committee considers it advisable to draw up such a code of electrical engineering ethics, to proceed with the work.

I believe as far as this motion goes it will be sufficient, if the committee nominated in this manner considers it inadvisable, to let the matter rest or take it up in annual convention next year. If, as I believe they will, they consider it advisable to proceed, then they can work at the subject tentatively and produce a code for submission to the members. The method of procedure then, I believe, would undoubtedly be the same which was successfully followed when we started the work of standardization; that is, a tentative code would be worked out by the committee, then submitted to a limited number of engineers in our organization for their opinions, suggestions, and criticisms, and after considering these opinions and suggestions and criticisms, the tentative code could be modified as far as the committee considered it advisable, and would then be submitted once more to the membership at large, to all the members, for their opinions, suggestions and criticisms; and after these suggestions and opinions are in and considered by the Code Committee, then the report would be resubmitted to the Institute at large, probably at the next annual convention.

Dugald C. Jackson: This is a matter that I have thought about frequently, on account of my relations with many young men with whom I am brought in close contact, and I take a great deal of pleasure in supporting the movement, which the President's address has so aptly given us a hint of, of getting together to do some more standardizing, and with that in view I wish to second the excellent motion of Dr. Steinmetz.

President Wheeler: The motion is made and duly seconded. It is now open for consideration. Are there any other remarks?

C. F. Scott: Our INSTITUTE has two general functions; one may be termed engineering activity, the publication of papers, the educational influence of the INSTITUTE among its members, and especially among the younger growing engineers of the country. The second function is a different function, which has aptly been emphasized during the past few days, and principally by the excellent address of President Wheeler, in which he emphasizes the importance of professional ethics in our INSTITUTE. At a meeting which was held last night, and to which I may have occasion to refer a little later, President Wheeler called renewed attention to the authoritative position which our INSTITUTE holds in the publication of its papers, through its Standardization Committee, and the like. We are not merely disseminating papers for their educational influence among our members, but we are disseminating literature which is accepted as standard, as representative of the profession. Even that which appears in the pages of our transactions, possibly presented as the individual views, or the results of work of a member, has a different standing when it appears on these pages from what it would have elsewhere. And in the shaping of the policies of the INSTITUTE for the future, these two things must be kept in mind. I have sometimes thought that those who have had one branch of the work of the INSTITUTE in mind, have minimized the importance of the other branch, or overlooked it; on the other hand, those who have had other things in mind have not seen the importance and realized the necessity of developing along other lines. I trust, therefore, the motion which has been made will be unanmously carried, as I believe it may be very useful in broadening and holding the proper balance between the different functions which our INSTITUTE should perform.

(President Wheeler put the motion, which was unanimously carried.)

President Wheeler: I need hardly say how glad I am to have the INSTITUTE take this step, because I think it is a very important matter for us all; and I am pleased to have the direction in which I have been thinking approved by my fellow members.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28, 1906.

REPULSION INDUCTION MOTOR.

BY MAURICE MILCH.

Of late the attention of electrical engineers has been frequently called to types of single-phase commutator motors combining the good characteristics of a repulsion motor at starting with the characteristics of a single-phase induction motor near synchronism; the idea being to produce a motor with good starting torque and limited speed, such as would be preeminently suited for tool, elevator, and similar work. In all these cases the combination mentioned has been brought about by a mechanical change, either gradual or sudden, in the armature circuits, this change being effected either by hand or by automatically operating centrifugal devices; in short, by means not inherent to the motor.

As a result of a study of the effect of differently distributed ampere-turns upon the action of the repulsion motor, some years ago the writer proposed a new type of motor in which starting characteristics similar to those of a repulsion motor were inherently combined with the near synchronous load characteristics of an induction motor.

In the following pages an attempt will be made to explain the action of this motor, supplementing the explanation with characteristic curves obtained from tests on motors built for commercial purposes.

I.

In order to facilitate the description of the apparatus, we shall first briefly consider the more or less known elements whose combined action makes for its success. These elements are: 1, the repulsion motor; 2, the commutator induction motor.

Fig. 1 represents the repulsion motor, and Fig. 2 the commutator induction motor. Both Figs. are self-explanatory and are simply referred to in Figs. 3 and 4.

Fig. 3 is the working diagram of the repulsion motor. In it I_1 represents the current and armature reaction of the primary member, supposed to be wound with a sinusoidally distributed winding; I_2, the current and armature reaction in the secondary member, (also supposed to be wound sinusoidally), the winding of which is short circuited by brushes *a a* displaced by the angle α from the reaction axis of the primary member. The vector combination—being allowed by the supposition of a sinusoidal distribution of the ampere-turns in both the primary and the secondary members—of both currents and reactions gives the resultant armature reaction, and consequently magnetic field, I_3. The action of this resultant field upon the secondary armature reaction produces a torque which creates a tendency in the motor to run away, similar to the direct-current series motor, as the torque-producing field is substantially proportional to the armature current.

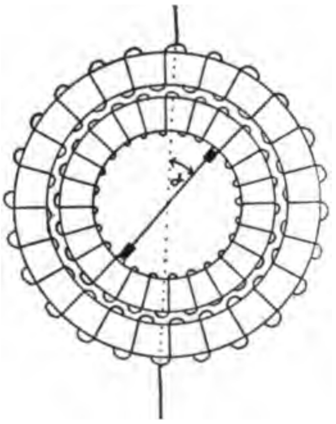

Fig. 1.

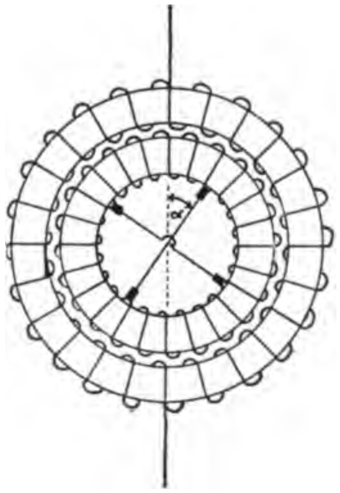

Fig. 2.

Fig. 4 is the working diagram of the commutator induction motor; *a a* are the primary terminals, *b b* are the brushes of the secondary "energy" circuit—in line with the primary circuit—and *c c* represents brushes of the secondary "compensating" circuit, displaced by 90 electrical degrees from the energy circuit. All circuits are supposed to be wound sinusoidally and to be without leakage.

It is to be seen at a glance that in contradistinction to the repulsion motor, this motor does not possess any starting torque whatever. For even if *b b* were displaced from *a a*, any sine-shaped field component perpendicular upon the energy circuit is completely damped out and annihilated by the compensating circuit *c c* which is short circuited upon itself and does not contain counter electromotive forces when at rest.

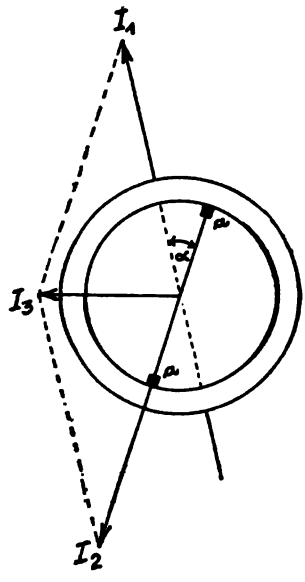

FIG. 3.

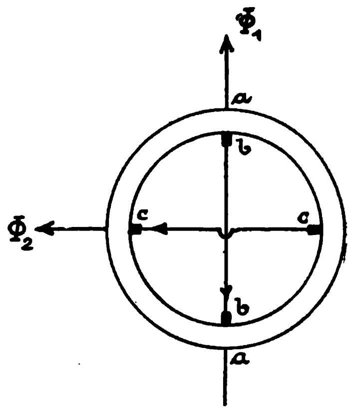

FIG. 4.

As soon, however, as the motor is set into motion a torque appears which first gradually increases and then decreases as the motor approaches synchronism, as may be seen from the following considerations:

Imagine, first, brushes *b b* open circuited, and the armature driven at synchronous speed, while an electromotive force E_1, Fig. 5, is impressed upon the primary terminals *a a*. This electromotive force creates a field Φ_1 in the direction of the primary circuit *a a* which lags by 90° behind E_1, and which by cutting the conductors of circuit *c c*, creates an electromotive force E_2 (in size equal to E_1), this in turn being in phase with Φ_1. As this electromotive force is short circuited upon the exciting impedance of circuit *c c*, a field Φ_2 is created by this circuit equal in size to, but displaced by 90°, in time and space, from Φ_1. Φ_1 and Φ_2, therefore, produce a revolving field at synchronous speed. Φ_2, by cutting the conductors of circuit *b b*, creates therein an electromotive force E_3 equal in magnitude and phase to E_1, or equal and opposite to the electromotive force E_1', induced between *b b* by the fluctuation of Φ_1. E_3 and E_1', therefore, cancel each other at synchronism, and *b b* may be short circuited without producing any current in this circuit. Below synchronism, however, $E_3 - E_1'$ is negative, and consequently a negative—motor—current will flow through *b b*; above synchronism, $E_3 - E_1'$ becomes positive, and a generator current—breaking—flows through *b b*. The motor, therefore, will behave like an ordinary induction motor. This description will hold good for the case that the secondary brush system is displaced from the primary axis of symmetry, as may be easily verified.

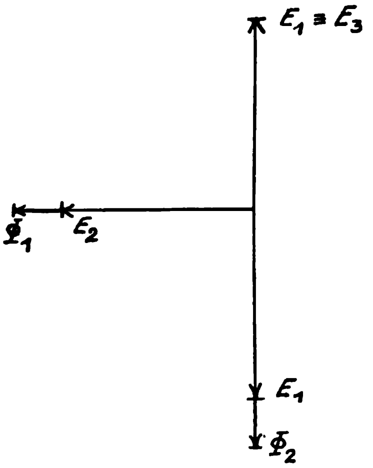

FIG. 5.

It will be seen, too, that the remarks on the commutator induction motor are also valid for the case of a non-sinusoidal distribution of ampere-turns along the gap, as long as they are distributed symmetrically around the primary axis; that is, as long as there is no brush displacement.

II.

Having described the two elements of the apparatus, it will now be shown that by simply choosing a particular distribution of ampere-turns along the gap of the motor, both elements can be combined in one apparatus.

Let Fig. 6 represent a 4-pole repulsion motor, whose armature is supposed to be of the Gramme type. Similarly, let Fig. 7 represent a 2-pole commutator induction motor, also equipped with a Gramme armature. In both figures the arrows represent the respective signs of the ampere-turns. If now the two armatures are rigidly coupled together and at the same time the primary members of both motors are connected in series, a combination is obtained that, due to its repulsion motor element, possesses a good starting torque and, due to its induction motor element, some of the load characteristics of such a motor near synchronous speed. For, when starting, the induction element will merely represent an impedance in series with the repulsion motor without adding any torque to the combination. With increasing speed, however, as has been seen, the impedance of the induction motor element rapidly increases, and consequently it will gradually drain the line voltage of the combination into its own circuits, thereby impressing upon the combination its own characteristics more and more as synchronism is approached.

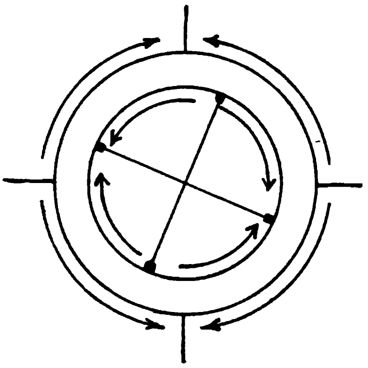

Fig. 6.

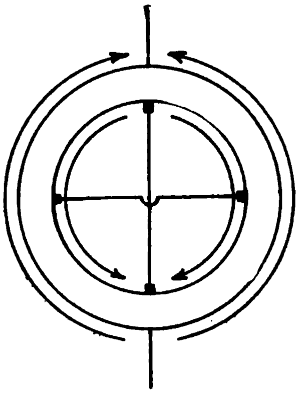

Fig. 7.

It was shown that the induction motor element does not possess any torque at synchronous speed. At this speed, however, the repulsion motor carries the magnetizing current of the commutator induction motor connected in series with it and, due to its consequent torque, drives the induction motor above synchronism up to a speed where the positive torque of the repulsion motor and the negative (generator) torque of the commutator induction motor balance each other. This speed, then, will be the limiting speed of the combination, and it will act as a motor below this speed and as a generator above it.

Instead of producing this effect by two separate structures. both elements may be blended into one. For this purpose the same armature is used—as the armatures are identical in both elements—and both primary windings are wound into the same slots above each other, Fig. 8. As seen in Fig. 8, equal and opposite current elements will then appear in some sections of both primary windings, thereby cancelling the effect of these sections and making them superfluous. Thus the arrangement shown in Fig. 9 will obviously be of the same effect as that of Fig. 8.

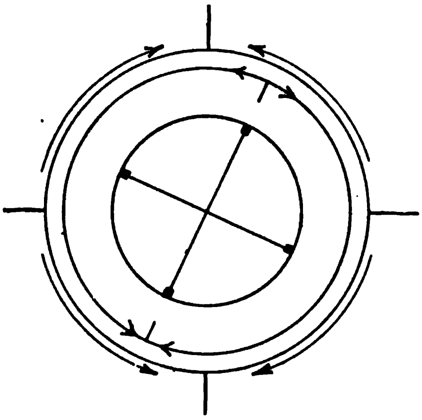

Fig. 8.

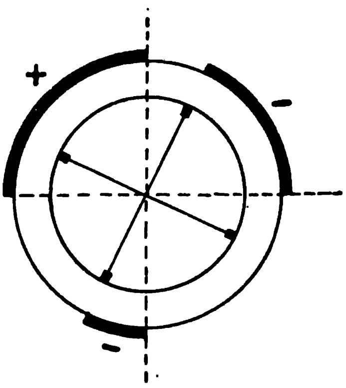

Fig. 9.

By a peculiar distribution of ampere-turns, an arrangement is now produced that possesses all the characteristics claimed for the repulsion induction motor—the significance of which term will now be apparent—at the outset of this paper, although owing to its peculiar mechanical makeup and its comparatively poor copper efficiency it will be merely of theoretical interest.

The principle of combining such elements naturally allows of quite a number of variations; as it is not worth while to discuss these in detail, only one case will be considered—a case of immediate practical importance, and which allows of a solution of the problem in an electrically as well as mechanically efficient way.

Imagine the periphery of a motor both in the primary and the secondary member wound with a sinusoidally distributed 2-pole winding. Fig. 10 shows this winding developed on a plane. Over this winding let there be wound a second winding of sinusoidal distribution, but of 3 x 2 poles, Fig. 11, and then another of 5 x 2 poles, etc., with decreasing amplitude of the distribution of conductors per unit length in the ratio of 1 for the 2-pole winding, 1/3 for the 6-pole winding, 1/5 for the 10-pole winding, etc. If all these windings are now connected in series there is obtained a winding which is equivalent to a 2-pole winding uniformly distributed over the circumference of the motor, as may be seen from the following consideration:

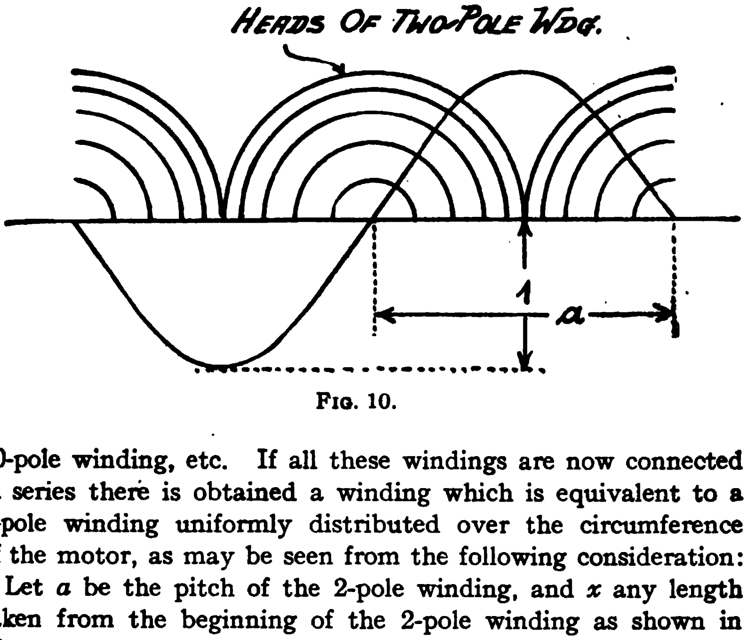

FIG. 10.

Let a be the pitch of the 2-pole winding, and x any length taken from the beginning of the 2-pole winding as shown in Fig. 11. Then, according to supposition, the number of conductors per unit length, y, at any point, x, will be

$$y = \sin \frac{\pi}{a} x + \frac{1}{3} \sin 3 \frac{\pi}{a} x + \frac{1}{5} \sin 5 \frac{\pi}{a} x + \ldots$$

This, however, according to Fourier, is equivalent to a rectilinear distribution of conductors whose number per unit length

—if 1 be the maximum number of conductors per unit length of the 2-pole sinusoidal winding—will be $\frac{\pi}{4}$. This, then, will be equivalent to any ordinary full-pitch winding in practical use to-day. Hence by winding the primary member with any full-pitch distributed winding, and the secondary member with any full-pitch drum winding, this will satisfactorily answer the conditions. And if the motor be provided with two sets of brushes, each set standing nearly perpendicularly upon the other, this combination will be similar in principle to the simple, but impractical, combination of a 2-pole induction, with a 4-pole repulsion motor as discussed above. The 2-pole sinusoidal windings of both primary and secondary members will then correspond to the commutator induction motor, whereas of the 6-pole, 10-pole, etc., windings each will be the repulsion motor element connected in series with the 2-pole commutator induction motor.

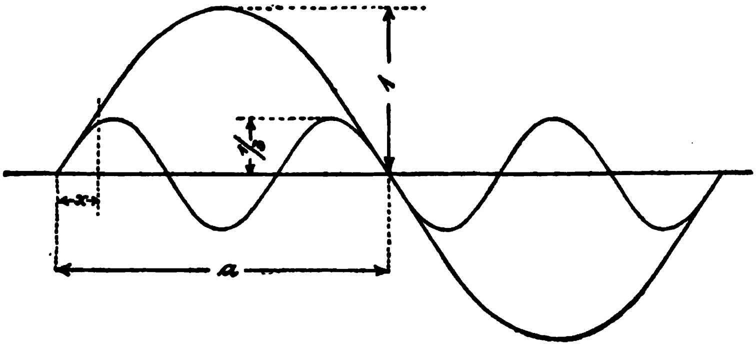

FIG. 11.

We now have obtained a motor which, with a simple full-pitch winding uniformly distributed over the circumference of the primary and the secondary members, will possess a good starting torque and a limiting speed somewhat above synchronism.

The description and explanation of Fig. 5 was made on the assumption of an ideal motor without internal impedance drop in its windings. In an actual motor the electromotive forces as shown in Fig. 5 will not balance each other so exactly, owing to leakage and resistance in the circuits. Hence the balancing of the electromotive forces will not be brought about by the prospective fields alone, and therefore, Φ_1 will be greater than Φ_2, unless the electromotive force E_2 be helped out by an additional electromotive force impressed by external means upon the compensating circuit, as has been proposed by Mr. Marius Latour. By a proper application of this auxiliary electromotive force, the motor may be so over-excited that it takes leading current from the line.

In the following considerations it will be assumed that a small auxiliary electromotive force is impressed upon the compensating circuit, this being the more general case. By making the impedance of the compensating circuit of suitable size, and different from the impedance of the energy circuit, it will be observed that an additional element enters into the method of operation of the motor. For it is clear that should the impedance of the compensating circuit become infinite, the motor would be reduced to a repulsion motor pure and simple. Thus by varying the magnitude of this impedance, the speed-torque characteristic of the motor may be varied at will, and it is to be seen that then a torque due to the 2-pole winding or fundamental harmonic will appear and become more and more prominent as the impedance increases.

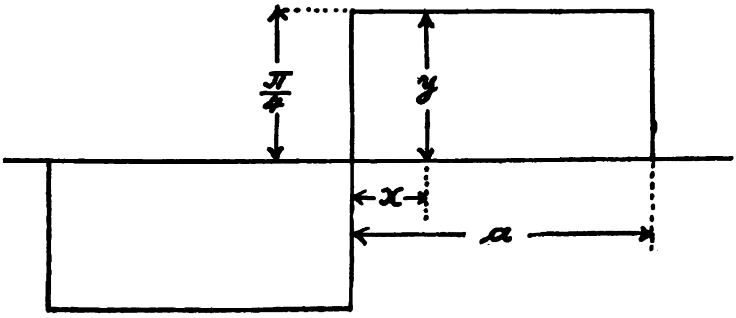

Fig. 12.

III.

A quantative analysis may now be made of the effects of a uniform distribution of ampere-turns upon the action of the motor. This analysis will be restricted to the conditions prevailing at starting, this being the most interesting point in question.

Imagine that according to Fourier's law we have decomposed the $2n$ polar uniformly distributed windings of both the primary and secondary members of a motor into the $2n$ polar, $6n$ polar, $10n$ polar, etc., sinusoidally distributed windings discussed above and that all these windings are connected in series in each individual member. Assume further that both

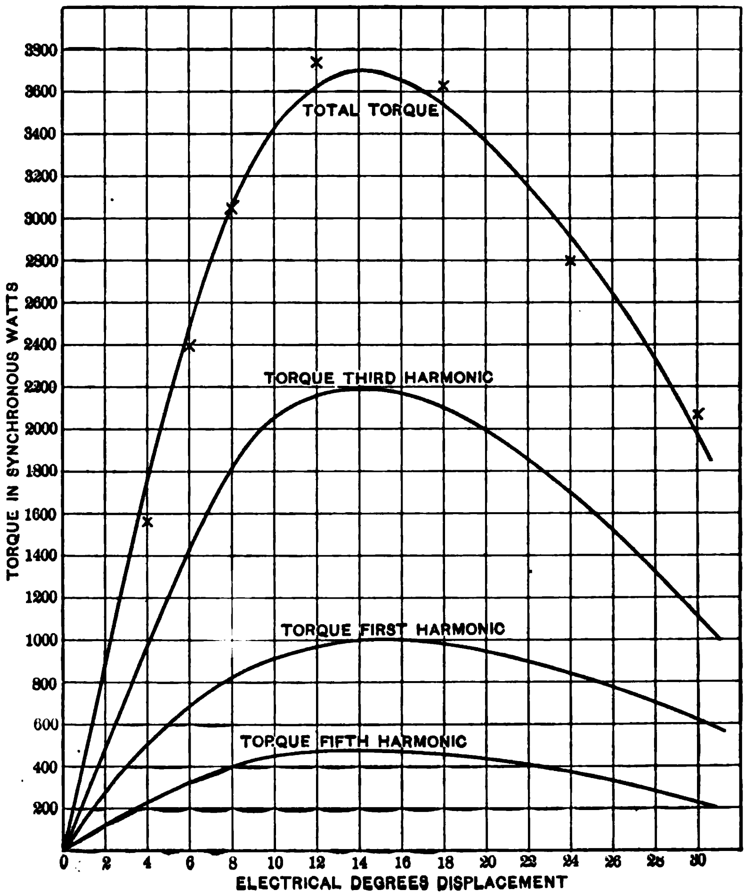

FIG. 13.

primary and secondary members carry the same number of turns.

Referring to Fig. 13, let:

Primary impressed electromotive force $= E_1$

Electromotive force impressed upon compensating circuit $= E_2$

Primary self-inductive impedance $= Z_1 = r_1 - j x_1$

Self-inductive impedance of secondary energy circuit = $Z_2 = r_2 - j\,x_2$

Self-inductive impedance of secondary compensating circuit = $Z_3 = r_3 - j\,x_3$

Mutual inductive impedance of actual, uniformly distributed winding = $Z_0 = -j\,x_0$

Mutual inductive impedance of the $2\,n$, $6\,n$, $10\,n$, etc., polar, sinusoidally distributed, windings corresponding to the first, third, fifth, etc., harmonics of the Fourier series = $Z_{\text{I}} = -j\,x_{\text{I}}$; $Z_{\text{III}} = -j\,x_{\text{III}}$; $Z_{\text{V}} = -j\,x_{\text{V}}$, etc.

Current in primary member = $I_1 = i_1' + j\,i_1''$

Current in energy circuit of secondary member = $I_2 = i_2' + j\,i_2''$

Current in compensating circuit of secondary member = $I_3 = i_3' + j\,i_3''$

By a simple calculation, as shown in the appendix, it is found that the mutual inductive impedances corresponding to the different harmonics are interconnected by the following relations:

$$Z_{\text{I}} = \frac{96}{\pi^4}\,Z_0 = R\,Z_0;\; Z_{\text{III}} = \frac{R}{3^4}\,Z_0;\; Z_{\text{V}} = \frac{R}{5^4}\,Z_0;\ \text{etc.}$$

The conditions in all three circuits to be satisfied are that the sum of all the electromotive forces be zero for each circuit.

Hence for the primary circuit in vector notation

$$(1)\quad E_1 = I_1\,(Z_1 + Z_{\text{I}} + Z_{\text{III}} + Z_{\text{V}} + \ldots) - I_2\,(Z_{\text{I}} \cos\alpha + Z_{\text{III}} \cos 3\,\alpha + \ldots) - I_3\,(Z_{\text{I}} \sin\alpha - Z_{\text{III}} \sin 3\,\alpha + Z_{\text{V}} \sin 5\,a - \ldots)$$

Similarly for the energy circuit of secondary member:

$$(2)\quad I_2\,(Z_2 + Z_{\text{I}} + Z_{\text{III}} + Z_{\text{V}} + \ldots) - I_1\,(Z_{\text{I}} \cos\alpha + Z_{\text{III}} \cos 3\,\alpha + \ldots) = 0$$

And for the compensating circuit:

$$(3)\quad I_3\,(Z_3 + Z_{\text{I}} + Z_{\text{III}} + Z_{\text{V}} + \ldots) - I_1\,(Z_{\text{I}} \sin\alpha - Z_{\text{III}} \sin 3\,\alpha + Z_{\text{V}} \sin 5\,\alpha - \ldots) + E_2 = 0$$

By definition: $Z_{\text{I}} + Z_{\text{III}} + Z_{\text{V}} + \ldots = Z_0$

Furthermore:

$$Z_I \cos\alpha + Z_{III} \cos 3\alpha + Z_V \cos 5\alpha + \ldots = Z_0 R \left(\cos\alpha + \frac{\cos 3\alpha}{3^4} + \frac{\cos 5\alpha}{5^4} + \ldots\right)$$

$$Z_I \sin\alpha - Z_{III} \sin 3\alpha + Z_V \sin 5\alpha - \ldots = Z_0 R \left(\sin\alpha - \frac{\sin 3\alpha}{3^4} + \frac{\sin 5\alpha}{5^4} - \ldots\right)$$

Substituting $A = R \sum_{n=1}^{n=\infty} \frac{\cos(2n-1)\alpha}{(2n-1)^4}$

$$B = R \sum_{n=1}^{n=\infty} (-1)^{2n-1} \frac{\sin(2n-1)\alpha}{(2n-1)^4}$$

into 1, 2, and 3, we get:

(4) $E_1 = I_1 (Z_1 + Z_0) - I_2 Z_0 A - I_3 Z_0 B$

(5) $I_2 (Z_2 + Z_0) - I_1 Z_0 A = 0$

(6) $I_3 (Z_3 + Z_0) - I_1 Z_0 B + E_2 = 0$

Hence:

(7) $$I_2 = I_1 A \frac{Z_0}{Z_2 + Z_0}$$

(8) $$I_3 = I_1 B \frac{Z_0}{Z_3 + Z_0} - \frac{E_2}{Z_3 + Z_0}$$

Inserting 7 and 8 into 4 we get:

$$E_1 = I_1 \left(Z_0 + Z_1 - A^2 \frac{Z_0^2}{Z_0 + Z_2} - B^2 \frac{Z_0^2}{Z_0 + Z_3}\right) + B E_2 \frac{Z_0}{Z_0 + Z_3}$$

or, denoting

$$C = Z_0 + Z_1 - A^2 \frac{Z_0^2}{Z_0 + Z_2} - B^2 \frac{Z_0^2}{Z_0 + Z_3},$$

we get:

$$(9) \qquad I_1 = \frac{E_1 - E_2 B \dfrac{Z_0}{Z_0 + Z_3}}{C} = i_1' + j\, i_1''$$

$$(10) \qquad I_2 = A \frac{Z_0}{Z_2 + Z_0} \; \frac{E_1 - E_2 B \dfrac{Z_0}{Z_0 + Z_3}}{C} = i_2' + j\, i_2''$$

$$(11) \qquad I_3 = B \frac{Z_0}{Z_3 + Z_0} \; \frac{E_1 - E_2 B \dfrac{Z_0}{Z_0 + Z_3}}{C} - \frac{E_2}{Z_3 + Z_0} = i_3' + j\, i_3''$$

Adopting Mr. Steinmetz's convenient expression of "torque in synchronous watts," synchronous speed is defined as the speed corresponding to the fundamental harmonic; that is, the speed of a $2n$ polar synchronous motor. In this same sense the actual synchronous speeds corresponding to the windings of the third, fifth, etc., harmonic will be called 1/3 synchronous, 1/5 synchronous, etc., speeds.

As the magnetic reluctance of the paths of mutual induction is supposed to be the same in all directions, it is obvious that visible torque effects will be produced between such magnetomotive forces only as are mechanically separated by the air-gap in addition to being perpendicular upon each other.

Accordingly, these active magnetomotive forces are decomposed into components perpendicular upon each other; considering them separately, the following relations are obtained:

Torque due to mutual action of magnetomotive forces I_2 and $I_1 \sin \alpha$ of the fundamental harmonic in synchronous watts

$$= x_1 \left(i_2' \, i_1' \sin \alpha + i_2'' \, i_1'' \sin \alpha \right)$$

Torque due to mutual action of magnetomotive forces I_3 and $I_1 \cos \alpha$ of the fundamental harmonic in synchronous watts

$$= - x_1 \left(i_3' \, i_1' \cos \alpha + i_3'' \, i_1'' \cos \alpha \right)$$

Hence total torque corresponding to the action of the first harmonic in synchronous watts =

$$(12) \qquad = x_{\text{I}} \left[(i_2' \, i_1' + i_2'' \, i_1'') \sin \alpha - (i_3' \, i_1' + i_3'' \, i_1'') \cos \alpha \right]$$

Torque due to mutual action of magnetomotive forces I_2 and $(I_1 \sin \alpha + I_3)$ of the third harmonic in 1/3 synchronous watts:

$$= x_{\text{III}} \left[i_2' \, (i_2' \sin 3\,\alpha + i_3') + i_2'' \, (i_1'' \sin 3\,\alpha + i_3'') \right]$$

Torque due to mutual action of magnetomotive forces I_3 and $(I_1 \cos \alpha - I_2)$ of the third harmonic in 1/3 synchronous watts:

$$= x_{\text{III}} \left[i_3' \, (i_1' \cos 3\,\alpha - i_2') + i_3'' \, (i_1'' \cos 3\,\alpha - i_2'') \right]$$

Hence total torque due to action of third harmonic in synchronous watts

$$(13) \quad = 3\, x_{\text{III}} \left[(i_2' \, i_1' + i_2'' \, i_1'') \sin 3\,\alpha + (i_3' \, i_1' + i_3'' \, i_1'') \cos 3\,\alpha \right]$$

Torque due to mutual action of magnetomotive forces I_2 and $(I_1 \sin 5\,\alpha - I_3)$ of the fifth harmonic in 1/5 synchronous watts:

$$= x_{\text{V}} \left[i_2' \, (i_1' \sin 5\,\alpha - i_3') + i_2'' \, (i_1'' \sin 5\,\alpha - i_3'') \right]$$

Torque due to mutual action of magnetomotive forces I_3 and $(I_1 \cos 5\,\alpha - I_2)$ of the fifth harmonic in 1/5 synchronous watts:

$$= - x_{\text{V}} \left[i_3' \, (i_1' \cos 5\,\alpha - i_2') + i_3'' \, (i_1'' \cos 5\,\alpha - i_2'') \right]$$

Hence total torque due to action of fifth harmonic in synchronous watts:

$$(14) \quad = 5\, x_{\text{V}} \left[(i_2' \, i_1' + i_2'' \, i_1'') \sin 5\,\alpha - (i_3' \, i_1' + i_3'' \, i_1'') \cos 5\,\alpha \right]$$

In a similar way the torque action of the still higher harmonics may be calculated and we obtain for the total torque in synchronous watts:

$$T = (i_2' \, i_1' + i_2'' \, i_1'') \left[x_{\text{I}} \sin \alpha + 3\, x_{\text{III}} \sin 3\,\alpha + 5\, x_{\text{V}} \sin 5\,\alpha + \,.\,. \right]$$
$$- (i_3' \, i_1' + i_3'' \, i_1'') \left[x_{\text{I}} \cos \alpha - 3\, x_{\text{III}} \cos 3\,\alpha + 5\, x_{\text{V}} \cos 5\,\alpha - \ldots \right]$$

Or, since:

$$x_{\text{I}} = R\, x_0; \; x_{\text{III}} = \frac{R}{3^4}\, x_0; \; x_{\text{V}} = \frac{R}{5^4}\, x_0; \text{ etc.,}$$

we have for the resulting torque in synchronous watts:

$$(15)\quad T = x_0 R \left[(i_2' i_1' + i_2'' i_1'') \sum_{n=1}^{n=\infty} \frac{\sin (2n-1)\alpha}{(2n-1)^3} \right.$$

$$\left. - (i_3' i_1' + i_3'' i_1'') \sum_{n=1}^{n=\infty} (-1)^{2n-1} \frac{\cos (2n-1)\alpha}{(2n-1)^3} \right]$$

IV.

In order to bring out the relative importance of the individual terms in the expression for the torque, and also to test their correctness by experiment, the curves shown in Fig. 13 have been calculated for a motor of the following constants:

$E_1 = 110$ volts.

$x_1 = 0.935$ $r_1 = 0.26$

$x_2 = 0.935$ $r_2 = 0.585$

$x_3 = 1.255$ $r_3 = 0.81$

$x_0 = 36$

The calculation has been carried out to the fifth harmonic only, as values obtained from the seventh harmonic are negligibly small, and as the character of the individual terms is elucidated well enough by the three component curves.

The curves represent calculated values, whereas the few points plotted were obtained from tests made by the prony brake. Each point plotted is the average of at least five readings. It will be seen that values obtained by test and calculation check fairly well, thereby proving also that harmonics above the fifth may be safely neglected.

Obviously, the higher the saturation in an individual case the more the results of calculation will differ from values obtained by test, as saturation tends to suppress the action of the higher harmonics.

In Fig. 14 are shown the speed-torque characteristics of a 5 h.p. 60-cycle motor that were obtained from test. As seen, the maximum torque in this case occurs at starting and gradually diminishes, falling to zero a few per cent. above synchronism. The values obtained for torque per kilovolt-ampere show that the motor is in this respect fully equivalent to a good polyphase induction motor with resistance regulation.

Fig. 15 shows results of a brake test on the same motor. The performance of the motor, according to these curves, compares very favorably with any other single-phase motor of this size, and at the same time points out very forcibly the commercial possibilities of the motor.

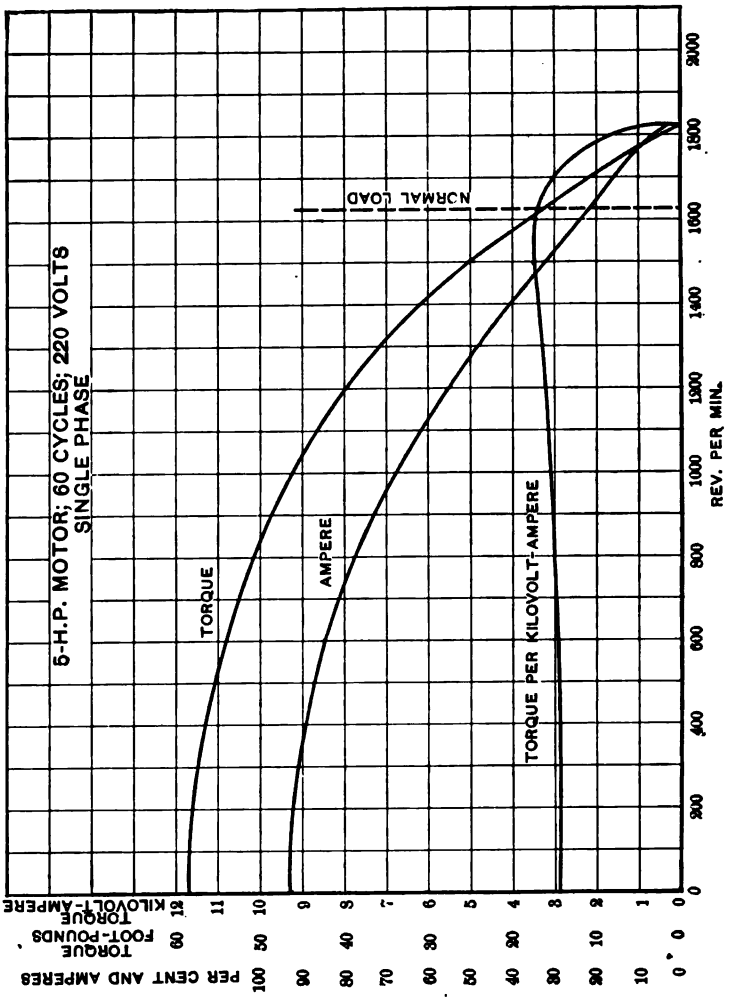

FIG. 14.

Objection may be made to the large slip at full load: but considering the application of this motor it would appear that this question is of very little importance in most cases. Should closer speed regulation be required in a particular case, a portion of the primary winding may be cut out at full speed so as to make the axis of the primary member practically coincide

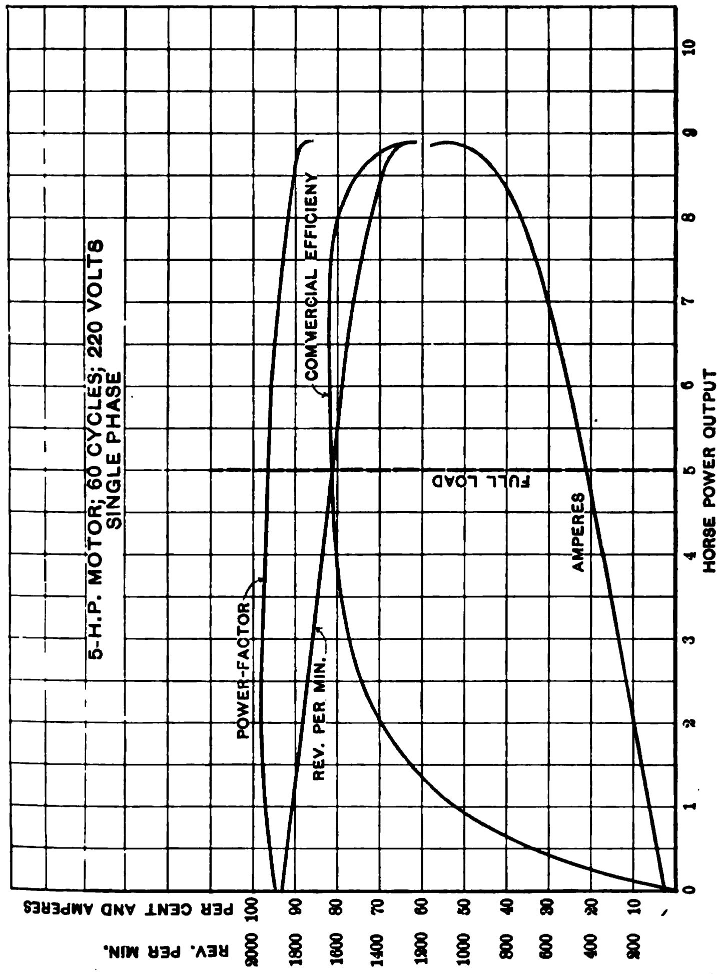

Fig. 15.

with that of the energy circuit. The slip will then be reduced to about three or four per cent.

In order to give an idea of how the performance of the motor changes as its size decreases, in Fig. 15 are shown characteristics of a 0.5-h.p., 60-cycle motor obtained from a brake test. The curves speak for themselves.

The commutation of both motors, in fact of all motors of the type built so far, compares quite well with that of

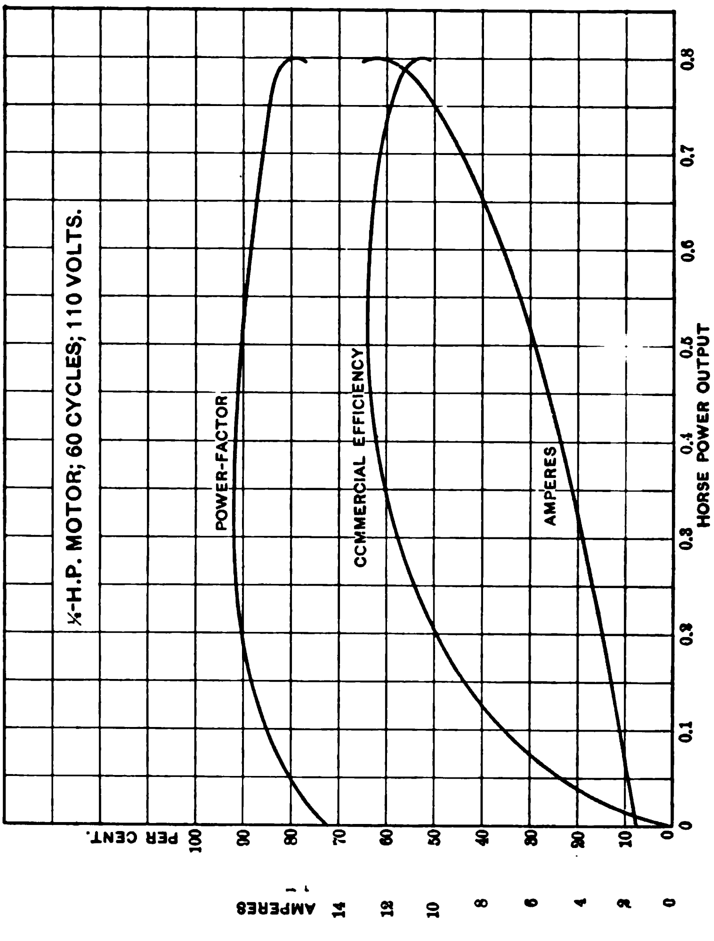

Fig. 16.

corresponding direct-current motors, and endurance tests have also shown that the commutator does not require more care.

The reason of the particularly good commutation of a motor of this type is apparent, as it is obvious that only a fraction of the torque-producing fields will be embraced by the coil that is short circuited under the brush.

For those further interested in the subject the writer takes the pleasure of referring to an interesting article by Mr. Seijiro Sugiyama,* who, working independently of the writer, establishes a similar theory with somewhat different results.

APPENDIX.

1. Exciting impedance of a winding with rectilinear distribution. Referring to Fig. 17, let

B_1 = maximum induction per square inch.
Z_1 = number of effective conductors per inch
C_1 = $4.44 \times \text{cycles} \times 10^{-8}$

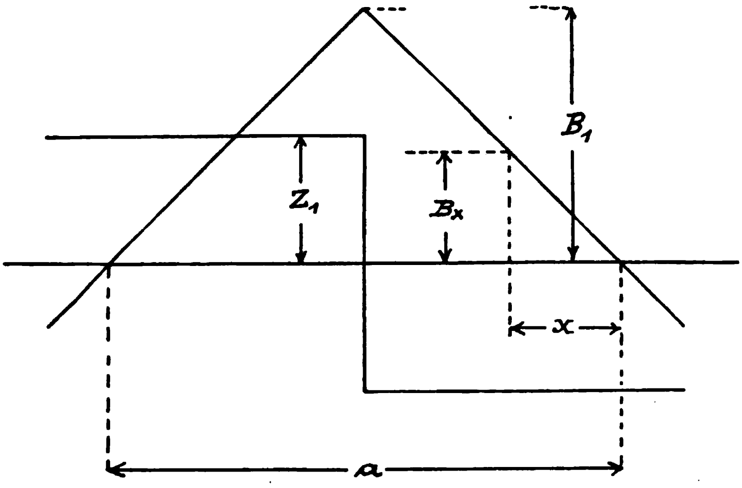

FIG. 17.

C_2 = a constant depending upon the magnetic reluctance
a = pole-pitch
Φ_x = flux per inch length of core
i_1 = exciting current
B_x = density at any particular point x
X_0 = exciting impedance per pole

Then, the electromotive force induced in the winding per pole and inch length will be:

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*Electrical World and Engineer, November 5th, 1904.

$$E_1 = C_1 \int_0^{\frac{a}{2}} \Phi_x n$$

where $$\Phi_x = (a - 2x) \frac{B_1 + B_x}{2} = B \left(\frac{a}{2} - \frac{2}{a} x^2 \right)$$

and $$n = Z_1 \, dx$$

Hence: $$E_1 = \frac{a^2}{6} B_1 Z_1 C_1$$

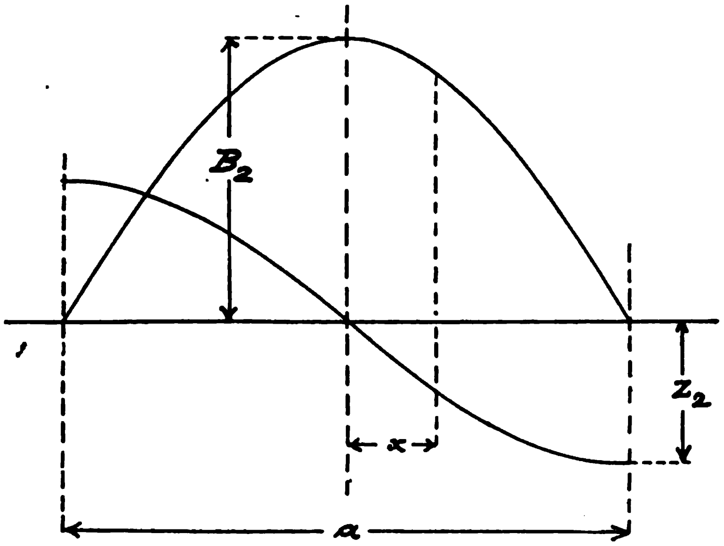

Fig. 18.

We have also: $$B = C_2 Z_1 a i_1$$

Hence, we have for the exciting impedance:

$$X_0 = C_1 C_2 \frac{a^3}{6} Z_1^2$$

2. Exciting impedance of a sinusoidally distributed winding. Referring to Fig. 18, let

B_2 = maximum density per square inch
Z_2 = number of maximum effective conductors per inch

Z_x = number of effective conductors per inch at any particular point
C_1 = 4.44 × cycles × 10^{-8}
C_2 = constant, depending upon the reluctance of the motor only
a = pole-pitch
Φ_x = flux per inch length of core
i_2 = exciting current
X_1 = exciting impedance
$n = Z_x\, d\, x$

Then, electromotive force per pole:

$$E_2 = C_1 \int_0^{\frac{a}{2}} \Phi_x\, n$$

$$\Phi_x = 2 \int_0^x B_2 \cos \frac{\pi}{a}\, x\, d\, x = \frac{2\, a\ B}{\pi^2} \sin \frac{\pi}{a}\, x$$

$$n = Z_x\, d\, x = Z_2 \sin \frac{\pi}{a}\, x\, d\, x$$

$$E_2 = C_1\ \frac{2\, a}{\pi} B_2\, Z_2 \int_0^{\frac{a}{2}} \sin^2 \frac{\pi}{a}\, x\, d\, x = C_1\, \frac{a^2}{2\, \pi} B_2\, Z_2$$

We also have:

$$B_2 = C_2 \frac{2}{\pi} Z_2\, a\, i_2$$

Hence:

$$E_2 = C_1 C_2\ \frac{a^3}{2\, \pi}\ \frac{2}{\pi}\ Z_2^2\, i_2$$

And

$$X_1 = C_1 C_2\, \frac{a^3}{\pi^2}\, Z_2^2$$

As the pole-pitch of the third harmonic is $\frac{a}{3}$, and as the maximum number of effective conductors per inch is $\frac{Z_2}{3}$, we get for the exciting impedance per three poles of the third harmonic:

$$X_{III} = 3\,C_1\,C_2\,\frac{1}{\pi^2}\,\frac{a^3}{3^3}\,\frac{Z_2^2}{3^2} = C_1\,C_2\,\frac{a^3\,Z_2^2}{\pi^2\,3^4},$$

And similarly for the exciting impedance of the fifth harmonic per 5 poles:

$$X_V = 5\,C_1\,C_2\,\frac{1}{\pi^2}\,\frac{a^3}{5^3}\,\frac{Z_2^2}{5^2} = C_1\,C_2\,\frac{a^3\,Z_2^2}{\pi^2\,5^4},\ \text{etc.}$$

Or, as from our supposition:

$$Z_2 = \frac{4}{\pi}\,Z_1,$$

we have:

$$X_1 = C_1\,C_2\,Z_1^2\,a^3\,\frac{4^2}{\pi^4}$$

$$X_{III} = C_1\,C_2\,Z_1^2\,a^3\,\frac{4^2}{\pi^4}\,\frac{1}{3^4}$$

$$X_V = C_1\,C_2\,Z_1^2\,a^3\,\frac{4^2}{\pi^4}\,\frac{1}{5^4}$$

etc. And, finally:

$$\frac{X_1}{X_0} = \frac{6 \times 4^2}{\pi^4} = \frac{96}{\pi^4} = R$$

$$\frac{X_{III}}{X_0} = \frac{R}{3^4}$$

$$\frac{X_V}{X_0} = \frac{R}{5^4}$$

etc.

DISCUSSION ON THE "REPULSION INDUCTION MOTOR," AT MILWAUKEE, WIS., MAY 28, 1906.

C. P. Steinmetz: I desire to draw your attention to some features of this paper. It is a report of the work done by my assistant, Mr. Milch, in developing a type of alternating-current motor intermediary between the polyphase induction motor and the single-phase series motor; that is, a motor having constant- and limited-speed characteristics combined with very high starting torque, and high torque efficiency and power-factor at starting and at low and intermediate speeds. The repulsion motor and the compensated series motor give a very high torque at starting and at low speeds, but an unlimited speed; that is, the speed increases indefinitely with decreasing load.

Such a motor, while eminently suited for electric railroad and similar classes of work, is not satisfactory for elevator work, hoisting, driving factory tool machines, etc.; for if the load were suddenly thrown off or reduced the motor would speed up and be liable to wreck itself or the driven machinery. Here the limited-speed motor is necessary.

The induction motor is a limited-speed motor, but in starting is decidedly inferior. It may be made to give a good starting torque efficiency by inserting a resistance in the rotor or secondary circuit. That, however, handicaps its utility for heavily fluctuating loads, because at loads it must run without the armature rheostat, and then a very heavy fluctuation of load may throw the motor out of step. For a very heavy sudden fluctuation of load, then, a motor is needed that increases in torque at good efficiency down to standstill, and not merely one that can be made to maintain its torque by operating the rheostat, but which by a series characteristic automatically raises its torque with decreasing speed and so spontaneously recovers.

As I have said, this motor is a combination of a series and a shunt motor. By compensation it gives very good characteristics. I call your attention to the curves in Figs. 14 and 15, where it is seen that the torque increases steadily down to standstill, the torque per kilovolt-ampere input remains constant, and the power-factor for variations of load is between 95% and 100%. The slip is naturally higher than with the induction motor. This motor combines a very high power-factor with high torque efficiency, limited speed, and heavy starting torque· but owing to the use of a commutator it has not quite the simplicity of the induction motor. It is, therefore, useful, and as a standard article of manufacture is being introduced for that class of work where its particular features are desirable; that is, for steady speed and steady load, as in cotton mills. Where continuous attention is given to the control, as in railway work, the induction motor and repulsion or compensated series motor respectively are the types of motor used. In other words, the repulsion induction motor forms an intermediate type between the induction and the series motor, a motor for electric elevators which is comparable to the direct-current compound motor as developed in the early days by Eickemeyer and used ever since by one of the electric elevator manufacturers.

D. C. Jackson: A number of years ago I was led to the conclusion that general power distribution could be better effected in the end by single-phase alternating currents than by our usual processes. That conviction led me to look into the question of a self-starting single-phase alternating-current motor which would have reasonably constant speed. I did at that time, and have since, given considerable attention to this question of a motor which includes, in one, some of the characteristics of a repulsion motor and some of the characteristics of an induction motor—a motor that starts like a repulsion motor and runs near synchronous speed more or less like an induction motor.

I believe that type of motor will, in the end, take the place of many of our polyphase motors for general power distribution. Undoubtedly the polyphase current has an advantage for long-distance transmission of power, and in cases where large motors may be used, on account of the way in which it utilizes the copper. In connection with such plants the polyphase motor is perhaps without a superior; but for general power distribution, the polyphase circuit and the polyphase motor are not entirely satisfactory, at least that is our experience in small plants in the central West. Doubtless, our past-presidents who sit upon the platform may be inclined to dissent from this assertion, but their experience has been more distinctively with plants so much larger than those which I more particularly refer to that we may perhaps be justified in having a difference in our points of view.

The development of the last few years has I think rather strengthened the conviction which I had some years ago, that single-phase circuits are the most desirable that have been developed for house to house distribution of power in the smaller cities. Under these circumstances I am pleased to read the paper by Mr. Milch in which he describes an interesting motor, and I shall add that the paper impresses me as being a beautiful discussion of the particular problem which he has had before him.

In my experiments I have found that the question of power-factor will take care of itself. The results of Mr. Milch's experiments seem to indicate the same fact. I have also found that the slip at full load could be controlled by fixing the distance above synchronism at which the machine runs at light load. Machines of this type run at a speed slightly above synchronism when lightly loaded, and the designer can fix that point; at full load they ordinarily run at a speed below synchronism. When I say synchronism, I mean a speed synchronous with the theoretical rotating field of a polyphase motor with the same number of poles working on a circuit at the same frequency. Consequently, since the point below synchronism at which the machine will take its full load, and the point above synchronism at which the machine will run at no load, can be practically fixed by design, the question of slip can be predetermined by the designer.

The specific form of motor described by Mr. Milch may not be an ultimate form; but self-starting, single-phase motors will, in the end, I am quite sure, be designed and manufactured of the *repulsion-induction* type. These will give satisfactory commercial characteristics, with regulation of speed equal to that in ordinary direct current motors and ordinary polyphase induction motors.

G. Percy Cole: This motor seems to have very large slip at full load. For this reason I think it would be rather objectionable for use in cotton mills, where constant speed is quite necessary. In the case of the 5-h.p. motor there is a slip of practically 15% between no load and full load; this would be rather objectionable in some classes of work. For elevators and machine tools where the drive does not require such close speed this motor might be suitable, but while the starting torque is very large the starting current is also very large. The starting torque is about four times the full-load running torque. If no means were introduced to control this current, it would have an objectionable effect on the distributing system. In this respect this motor is not so good as a true repulsion motor which, when thrown on full line voltage, takes a starting current of about 2.5 times the full-load running current, and the starting torque is about 2.5 times the full-load running torque.

It seems to me that this motor would not be so suitable as other forms of single-phase induction motors. Take for example the Arnold type of single-phase induction motor, where every segment of the commutator is short-circuited when up to running speed, Such a good short circuit is obtained on the armature that there is better speed regulation than on the polyphase induction motor. On a 5-h.p. Arnold type of motor the slip at full load is between 2.5% and 3%. A polyphase induction motor of the same capacity would have about 5%, whereas this motor before us to-day has practically 15%. The following statement is made in the paper:

> Objection may be made to the large slip at full load, but considering the application of this motor it would appear that this question is of very little importance.

But it does not mention what this motor is supposed to be used for. I should judge that it is for elevator work and work where heavy starting torque is required. For elevator work, however, there is another motor known as the Schuler type, in which the short-circuiting is done through a controller. The full-load slip of a motor of this kind is only about 3.5% on a motor of from 5 to 10 h.p. The starting current can be controlled within 50% over full-load current and still at the same time give 50% over full-load torque.

Another objection to the Milch type of motor, used for constant-speed work, is that the brushes remain on the commutator all the time, and consequently have a wear and tear comparable to that on the brushes of a direct-current motor. The Arnold type of motor in use now does not have the brushes bear on the commutator at all during normal operating conditions, because as the armature is short-circuited the motor runs purely as a single-phase induction motor.

C. P. Steinmetz: High starting torque necessarily means greater slip at full-load running. But wherever very high torque is required at low and intermediate speeds, a greater slip is permissible. In a cotton mill, which requires very steady speed, you do not require heavy starting torque and good power-factor at intermediate speeds, and do not require the ability to recover at excessive overloads because these never occur. And, first and last, a commutator is not wanted in a cotton mill; that is the reason why, in a cotton mill, the plain induction motor is preferred to any type of commutator motor, whether direct current or alternating. With a commutator, there is always the possibility of a slight arc, and with the space filled with floating lint this arc is a dangerous thing. The heavy starting torque in this motor, three to four times the running torque, means three to four times the running current. The repulsion or series motor, to get the same starting torque, does not require so much current; that is, the repulsion or series motor is not only equal, but superior to this motor in starting. The constant-speed characteristics mean some sacrifice in starting current.

The polyphase induction motor without secondary resistance is inferior in starting-torque efficiency, requiring several times more current for a certain starting torque than for the same torque when running. With armature resistance, the polyphase induction motor gives the same torqu peer ampere when starting as when running, but cannot well be built to give three to four times running torque in starting without badly spoiling the power-factor when running at part load. Mechanical combinations of induction and repulsion motor have the objection that if the centrifugal device which cuts out the commutator should fail at light load, the motor would race and wreck things.

I do not consider the present, nor any other motor as a universal motor. I do not share Professor Jackson's idea that the universal motor will be a single-phase limited-speed motor. I have been a strong advocate of the single-phase system, but I am not quite so strongly in favor of it now. As a result of the change in industrial conditions during the last few years, I am leaning toward the polyphase system, for reasons which we have no time to discuss now.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, May 28-31, 1903.

COMPARISON OF TWO- AND THREE-PHASE MOTORS.

BY BRADLEY MCCORMICK.

In the manufacture of induction motors considerations of cost make it advisable to build both two- and three-phase motors on the same size of frame. The questions then arise, given two similar frames without windings, how shall the two- and three-phase windings differ in order to secure proper operation? What will be the comparative losses if both machines are given the same rating, or, if not rated the same, how shall their ratings differ?

The answer to these questions involves a comparison of the following factors in two- and three-phase machines:

1. Distribution factor, which takes into account the effect on the voltage of distributing the windings into a number of slots.
2. Flux-variation factor, which shows how nearly the field conforms to the perfect sinusoidal revolving field.
3. Current density in rotor and stator.
4. Leakage factor.

DISTRIBUTION FACTOR.

Suppose the conductors are wound in four slots per phase per pole and let the four equal pressures $O A$, $O B$, $O C$, and $O D$, each α degrees behind the other, represent the pressure generated in each slot (see Fig. 1). Complete the polygon of electromotive forces, and $O D'$ is the resultant pressure. Now, evidently the polygons $O A B' C' D'$ and $A B C D E$ are similar. The pressure, if all the coils were concentrated in one slot, would be $OA+OB+OC+OD$ instead of OD' so we may write,

$$K = \frac{OD'}{OA+OB+OC+OD} = \frac{AE}{AB+BC+CD+DE} = \frac{AE}{bP}$$

$$= \frac{2\,V \sin \frac{1}{2}\,\alpha\, b}{2\,V\, b \sin \frac{1}{2}\,\alpha} = \frac{\sin \frac{1}{2}\,\alpha\, b}{b \sin \frac{1}{2}\,\alpha}$$

where K = the distribution factor
V = the pressure generated per slot
b = number of slots per phase per pole.
when b becomes infinite, $b\,p$ becomes arc $A\,E$ and

$$K = \frac{2 \sin \frac{1}{2} < AOE}{2\,\pi \dfrac{< AOE}{360}}$$

Table 1 shows the values of distribution factor for various cases.

TABLE I.

Slots per phase per pole	Three-phase.	Two-phase.
1	1.	1.
2	0.966	0.924
3	0.960	0.911
4	0.958	0.906
5	0.957	0.904
6	0.956	0.903
Infinity.	0.955	0.901

Let E = volts across lines
Φ = flux per pole
$\sim$ = frequency in cycles per second
a = conductors per phase per pole = $b\,s$
b = slots per phase per pole
s = conductors per slot
K = distribution factor
p = number of poles
n = number of phases
The flux is given by the relation

$$\Phi = \frac{10^8\,E}{2.22\,K\,p \sim a} \text{ and } a = \frac{10^8\,E}{2.22\,K\,p \sim \Phi} = b\,s$$

Compare now a two- and a three-phase machine having 12 slots per pole, and suppose that the three-phase machine is Y connected. In the two-phase machine $b = 6$ and in the three-phase machine $b = 4$. We then have the following:

two-phase $\qquad\qquad$ three-phase

$$6\,s' = \frac{10^8\,E}{2.22\,p \sim \Phi\ .903} \qquad\qquad 4\,s = \frac{10^8\,E}{\sqrt{3}\,2.22\,p \sim \Phi\ 0.958}$$

$$\frac{s'}{s} = \frac{4}{6} \times \frac{\sqrt{3}.958}{0.903} = 1.225$$

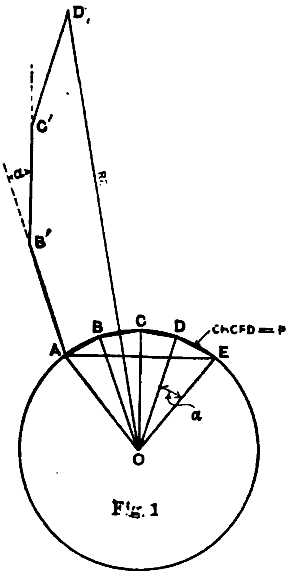

Fig. 1

So that for the same flux a two-phase machine should have 22.5 per cent. more conductors per slot than a three-phase Y-connected machine.

FLUX VARIATION FACTOR.

Suppose we have a winding with n phases and a conductors per phase per pole. The current distribution along the winding at all points follows the sine law, so that if a and n are large we may represent the instantaneous value of current by the smooth curve shown in Fig. 2. Consider now a group of conductors in which the currents all flow in the same direction, for example those designated by the (+) plus sign. The magnetomotive force at any point, such as $B\ B$, is the difference between the ampere conductors to the right and those to the left of $B\ B$, but in the same group. This fact defines the curve of magnetomotive force whose ordinates are in ampere-turns *per pair of poles*. At $A\ A$ the magnetomotive force will be that due to all the $a\,n$ conductors in the group to the right, that is, $a\,n$ times the average value of current in the group

$$a\,n\left(I\sqrt{2}\times\frac{2}{\pi}\right)=0.9\,a\,n\,I$$

This is the ideal value (expressed in ampere-turns per pair of poles) of magnetomotive force at the maximum point in the wave of magnetomotive force. All polyphase revolving fields approach more or less this maximum value, the agreement being closer and closer as a and n approach infinity.

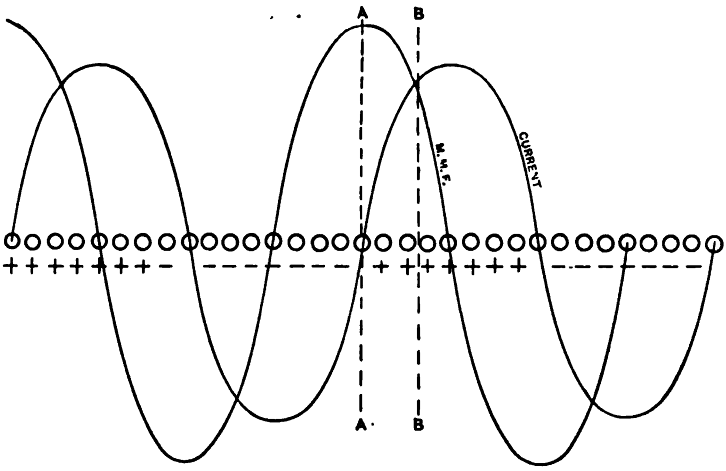

Fig. 2

In all cases which are met in practice, the maximum magnetomotive force should be expressed as $0.9\,K'\,a\,n\,I$, where K' is the variation factor to which reference has already been made. By plotting the magnetomotive-force curve for several actual cases, it is possible to obtain the law of field variation from which the values of K' may be easily calculated for all cases.

Fig. 3a shows an irregular curve obtained from a three-phase winding with 6 slots per pole per phase at the point when the current in the first and third phases equals half the current

THREE PHASE - 6 SLOTS PER POLE PER PHASE.

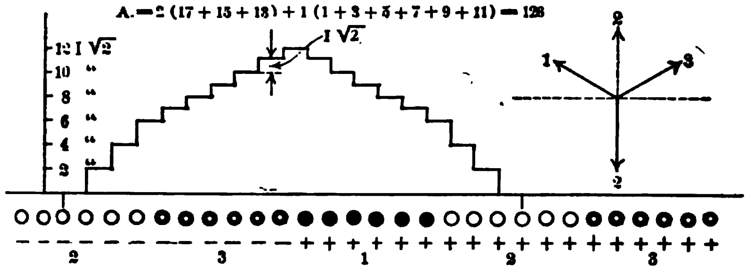

Fig. 3a

THREE PHASE - 6 SLOTS PER POLE PER PHASE.

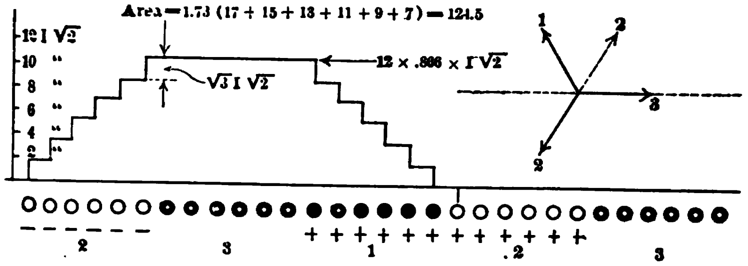

Fig. 3b

THREE PHASE - 5 SLOTS PER POLE PER PHASE.

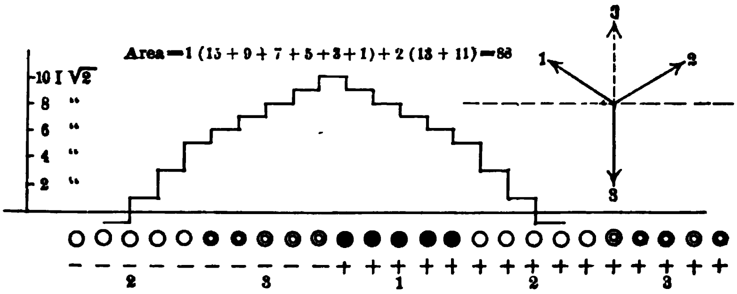

Fig. 4a

THREE PHASE - 5 SLOTS PER POLE PER PHASE.

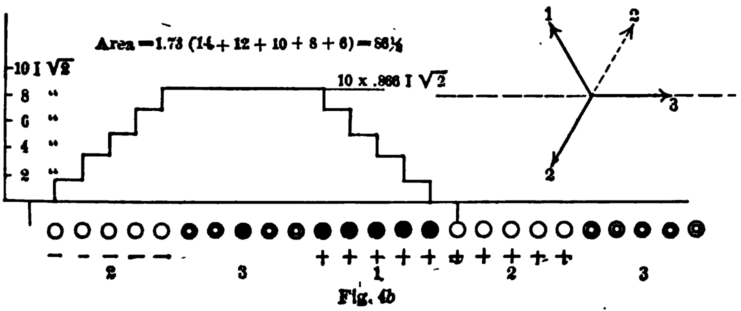

Fig. 4b

in the second phase. Fig. 3b shows the shape of the curve 30 degrees later when the third phase is zero. It will be noticed that there is considerable variation between the maximum ordinates, although the areas differ but slightly

The area of the curve in Fig. 3a is,

$$A = 2\,(17+15+13)+(1+3+5+7+9+11) = 126$$

and the area of the curve in Fig. 3b is

$$B = 1.73\,(17+15+13+11+9+7) = 124.5$$

The average area is $\frac{A+B}{2} = 125.25$

Replacing the curves by a sine curve having an area equal to the mean value of A and B, we get as its average ordinate,

$$\frac{\frac{A+B}{2}\,I\sqrt{2}}{a\,n}$$

and as its maximum value,

$$\frac{\frac{A+B}{2}\,I\sqrt{2}}{a\,n}\;\frac{\pi}{2} = 0.9\,a\,n\,I\,K'$$

Solving for K' gives,

$$K' = \frac{A+B}{a^2n^2}\,1.2344$$

For six slots per phase per pole K' becomes,

$$\frac{126+124.5}{6^2\times 3^2}\times 1.2344 = 0.9569$$

Curves have also been plotted for two-phase windings for the extreme cases; first with both phases equal and then one phase at a maximum and the other at zero.

By examining Figs. 3, 4, 5, and 6, it will be seen that for any case A and B will be given by the following expressions:

three-phase—b even.

TWO PHASE-6 SLOTS PER PHASE PER POLE

Area $=\sqrt{2}\,(11+9+7+5+3+1)=50.904$

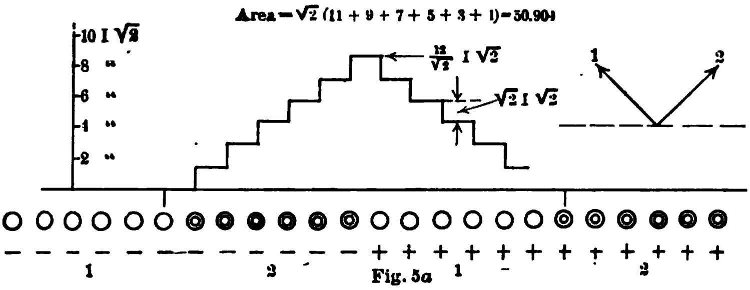

Fig. 5*a*

TWO PHASE-6 SLOTS PER PHASE PER POLE

Area $=2\,(11+9+7)=54$

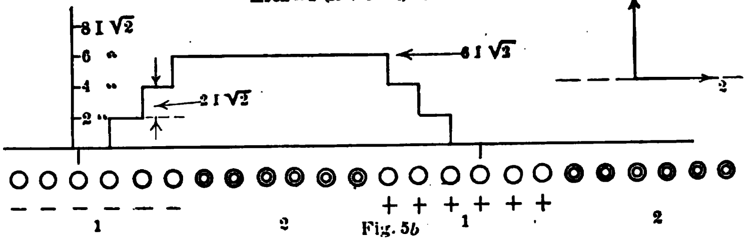

Fig. 5*b*

TWO PHASE-5 SLOTS PER POLE PER PHASE

Area $=\sqrt{2}\,(9+7+5+3+1)=35.4$

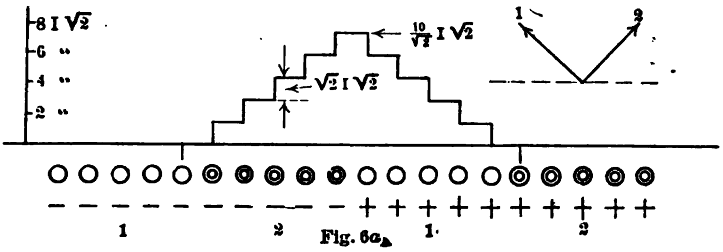

Fig. 6*a*

TWO PHASE-5 SLOTS PER POLE PER PHASE

Area $=2\,(8+6)+1\,(10)=38$

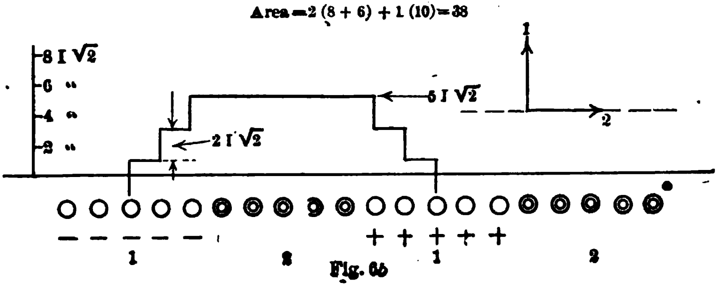

Fig. 6*b*

$$A = 2\left\{[3b-1]+[3\,b-3]+[3\,b-5] \text{ to } \frac{b}{2} \text{ terms}\right\} + \left\{1+3+5+7 \text{ to } b \text{ terms}\right\}$$

$$B = 1.73\ \left\{[3\,b-1]+[3\,b-3]+[3\,b-5] \text{ to } b \text{ terms}\right\}$$

three-phase—*b* odd

$$A = 3\,b + \left\{[1+3+5+7 \text{ to } b \text{ terms}] + 2\ \left\{[3\,b-2]+[3\,b-4] + [3\,b-6] \text{ to } \frac{b-1}{2} \text{ terms}\right\}\right.$$

$$B = 1.73\ \left\{[3\,b-1]+[3\,b-3]+[3\,b-5] \text{ to } b \text{ terms}\right\}$$

two-phase—*b* even.

$$A = \sqrt{2}\left\{[2\,b-1]+[2\,b-3]+[2\,b-5]\ldots\ldots\ldots 1+\right\}$$

$$B = 2\ \left\{[2\,b-1]+[2\,b-3]+[2\,b-5] \text{ to } \frac{b}{2} \text{ terms}\right\}$$

two-phase—*b* odd.

$$A = \sqrt{2}\left\{[2\,b-1]+[2\,b-3]+[2\,b-5]\ldots\ldots\ldots +1\right\}$$

$$B = 2\,b + 2\ \left\{[2\,b-2]+[2\,b-4]+[2\,b-6] \text{ to } \frac{b-1}{2} \text{ terms.}\right\}$$

Reference to table 2 shows that in three-phase machines with an odd number of slots per phase per pole, K' is constantly decreasing and approaches a constant value of 0.9569 when b is infinity. When b is even, $K' = 0.9569$ regardless of the magnitude of b. Similar characteristics will be found in two-phase machines, except that K' approaches 0.9.

The maximum value of induction corresponding to the maximum in the equivalent sine curve of magnetomotive force is

$$B = \frac{3.19 \times 0.9\ a\ n\ I_0 K'}{2\,\varDelta} = B = \frac{1.435\ \ a\ n\ I_0\ K'}{\varDelta}$$

$$\varPhi = B\,\tau\,L\,\frac{2}{\pi} = \frac{2}{\pi}\,\tau\,L \times \frac{1.435\ a\ n\ I_0\ K'}{\varDelta}$$

$$I_0 = \frac{\pi\,\varPhi}{2\,\tau\,L}\ \frac{\varDelta}{1.435 \times n\ a \times K'}$$

THREE PHASE.

b	A		B		A+B	K′
1	3+1	4	1.73 (2)	3.46	7.46	1.023
2	2 (5)+(1+3)	14	1.73 (5+3)	13.84	27.84	0.9569
3	9+(1+3+5)+2 (7)	32	1.73 (8+6+4)	31.1	63.1	0.9624
4	2 (11+9)+(1+3+5+7)	56	1.73 (11+9+7+5)	55.4	111.4	0.9569
5	15+(1+3+5+7+9)+2 (13+11)	88	1.73 (14+12+10+8+6)	86.5	174.5	0.9587
6	2 (17+15+13)+.1+3+5+7+9+11)	126	1.73 (17+15+13+11+9+7)	124.5	250.5	0.9569
	Infinity. $2b\times b+.5\times 2b\times b+b\times .5b=$	$3\frac{1}{2}b^2$	$0.866\times 2b\times 2b$	3.46462	$6.964b^2$	0.9569

TWO PHASE.

b	A		B		A+B	K′
1	$\sqrt{2}(1)$	1.414	2	2	3.414	1.052
2	$\sqrt{2}(3+1)$	5.66	2 (2)	6	11.66	0.9
3	$\sqrt{2}(5+3+1)$	12.7	2 (3)+2 (4)	14	26.7	0.9174
4	$\sqrt{2}(7+5+3+1)$	22.6	2 (7+5)	24	46.6	0.9
5	$\sqrt{2}(9+7+5+3+1)$	35.4	2 (5)+2 (8+6)	38	73.4	0.909
6	$\sqrt{2}(11+9+7+5+3+1)$	50.9	2 (11+9+7)	54	104.9	0.9
	Infinity. $0.5\sqrt{2}b\times 2b$	$\sqrt{2}b^2$	$b\times 1\frac{1}{2}b$	$1.5b^2$	$2.94b^2$	0.9

Where I_0 = magnetizing current
τ = pole-pitch
Δ = single air-gap in inches (effective)
L = axial length of machine
B = maximum flux density in gap in lines per sq. in.

For a three-phase machine with four slots per phase per pole,

$$I_0 = \frac{\pi \Phi}{2 \tau L} \cdot \frac{\Delta}{1.435 \times 3\, a \times .9569} = \frac{\Phi \Delta}{2.62\, a \tau L}$$

For a two-phase machine with 6 slots per phase per pole,

$$I_0 = \frac{\pi \Phi}{2 \tau L} \cdot \frac{\Delta}{1.435 \times 2 \times a \times 0.9} = \frac{\Phi \Delta}{1.65\, a \tau L}$$

In the three-phase machine $a = s \times 4$ and in the two-phase $a = s \times 1.225 \times 6$

$$I_0 \text{ three-phase} = \frac{\Phi \Delta}{2.62 \times 4 \times s \tau L} = \frac{\Phi \Delta}{10.48\, \tau L s}$$

$$I_0 \text{ two-phase} = \frac{\Phi \Delta}{1.65 \times 1.225 \times 6 s \tau L} = \frac{\Phi \Delta}{12.1\, \tau L s}$$

The magnetizing current in a three-phase machine is approximately 15 per cent. more than in the two-phase.

The load current of the three-phase machine is $\frac{2}{\sqrt{3}}$ times that of the two-phase machine; *i.e.*, 15 per cent. more; that is, the magnetizing current is the same when expressed in per cent. of full load current both in the two-phase and three-phase machines. This, of course, assumes the same apparent efficiency in each case.

CURRENT DENSITY.

It has been shown that for the same value of flux we need 1.22 times as many conductors in the two-phase machine as are required for the three-phase Y-connected motor of the same voltage. Considering the insulation space factor the same in each case, the two phase machine will have $\frac{1}{1.22}$ times the copper area.

As the current in the two-phase machine is $\frac{\sqrt{3}}{2} = 0.866$

times that of the three-phase machine, it follows that the current density of the two-phase machine is $0.866 \div \frac{1}{1.225} = 1.06$ times the current density in the three-phase machine and the copper loss is $(1.06)^2 = 1.123$ times as great, or, roughly, the copper loss is 12% greater in the two-phase machine.

LEAKAGE FACTOR.

The leakage in a squirrel-cage induction motor may be said to consist of four components, stator-slot leakage, stator free-end leakage, rotor-slot leakage, and rotor free-end leakage. Since the leakage factor is so complicated in its make up, it is impracticable to compare the leakage factors of two- and three-phase machines by means of mathematical formulas.

Tests of a number of machines show that the leakage factor of a two-phase machine is from 20 to 30 per cent. higher than on the same machine wound for three-phase service, the variations depending upon the relative magnitude of the four components which go to make up the total leakage. As a fair average, the leakage factor of a two-phase motor may be taken at about 25 per cent. larger than that of the same machine wound for three phases.

SUMMARY.

The following are the principal points brought out in this article relative to two- and three-phase machines, and will aid the designer in deciding upon the proper ratings for machines when wound for two-phase service.

1. A two-phase machine should have 22 per cent. more conductors per slot than the corresponding three-phase Y-connected machine designed for the same voltage and flux per pole.
2. The magnetizing current is the same in both two- and three-phase machines, when expressed in per cent. of the current which corresponds to the full-load output.
3. The copper loss of the two-phase machine is 12 per cent. higher than that of the three-phase.
4. The leakage factor of the two-phase machine averages 25 per cent. greater than that of the three-phase machine.

Even machines of the same phase and rating, which are made as nearly alike in every respect as is commercially possible, vary widely among themselves in their characteristics when put in test. This fact makes it very difficult to determine by test the relative behavior of two- and three-phase machines, especially with regard to those characteristics which differ but slightly. There can be no doubt as to the higher temperature rise of the copper in the two-phase motor, occasioned by the higher copper loss. For the same reason the efficiency of the two-phase motor is slightly lower, the difference depending upon the relative magnitude of the iron and copper losses. Since the slip is equal to the ratio of the secondary copper loss to the total power input to the secondary, it is evident that the slip is greater on the two-phase motor. Calculations and tests indicate that the slip on two-phase motors is about 20 per cent. greater than in three-phase motors. Due to the increased leakage, the power-factor on the two-phase machine is from 1 to 3 per cent. lower than on the three-phase motor.

DISCUSSION ON "COMPARISON OF TWO- AND THREE-PHASE MOTORS," AT MILWAUKEE, WIS., MAY 28, 1906.

A. S. McAllister: The author says that the magnetizing current in a three-phase motor is approximately 15 per cent. more than that in a two-phase motor, but that when expressed in per cent. of the full-load current the magnetizing currents of the two motors are equal. These statements are based on a study of the distribution of the primary coils, of the change in the value of the magnetizing current, and of the fluctuation in magnetism produced thereby.

I wish to call attention to the fact that these relations may be established much more simply without any reference whatever to the numerous factors which the author has taken into consideration, other than his original implied assumptions that the frames of the two motors are equal and are subjected to the same iron losses.

Although it would be possible to determine the components of the primary current necessary to supply the hysteresis loss by ascertaining the distribution of the coils, the path assumed by the flux, and then making an elaborate study of the B-H curve of the iron employed, such a laborious method is considered entirely unnecessary, and use is made of the familiar hysteresis formula:

$$W_h = h f B_m^{1.6} V$$

where h is a constant depending upon the quality of the iron. Similarly the eddy-current loss is found from the formula:

$$W_e = e f^2 d^2 B_m^2 V$$

The sum of these two quantities gives the iron loss in watts, and the current to supply these losses is found by dividing this value of watts by the impressed electromotive force.

It can easily be shown that with a closed magnetic circuit the quadrature exciting watts may be expressed by the formula:

$$W_q = q f B_m^2 \frac{V}{\mu}$$

where μ is the permeability of the iron and q is a constant, having a value of

$$q = \frac{2.5}{10^8}$$

When an air-gap is inserted in the magnetic path, the quadrature watts may be expressed by the formula:

$$W_q = q f B_m^2 \left(\frac{V}{\mu} + V_a\right)$$

where V_a is the volume of the air-gap. The exciting current is found by dividing W_q by the impressed electromotive force.

Where there are divided magnetic circuits and the magnetism is not uniform throughout the paths, it is desirable to consider each path separately, just as is true in treating the hysteresis and the eddy losses. An inspection of the formula for expressing the quadrature watts will show that if the effective value of the maximum magnetic density throughout the several volumes be used, a correct result will be obtained from a single calculation.

From the above discussed facts it will be evident that the quadrature exciting watts of an induction motor operated at a certain frequency and magnetic density depends solely on the volume of the core and the air-gaps, and is not affected by the number coils or phases or the voltage of the machine.

These remarks should not be considered as adverse criticism of the paper under discussion. On the contrary the speaker wishes to express his appreciation of the clear manner in which the matter has been presented, and of the value of the paper to a practising designer. He wishes merely to make a plea for simplicity in the treatment of electric phenomena in all cases where elaborations do not contribute to the accuracy of the results obtained.

Bradley McCormick: Mr. McAllister's method strikes me as being very good. I have employed the same method in the case of transformers, and find it works admirably; but just why I use this method instead of the other in the induction motor I can explain only by saying that it has become a matter of custom. A designer employs one method in preference to another largely through habit.

C. P. Steinmetz: I do not quite agree with the conclusion that such a considerable difference exists between the three-phase and the two-phase induction motor, in favor of the three-phase motor. This does not agree with my experience, theoretical and experimental. The exciting volt-amperes of an induction motor at constant magnetic density; that is, constant magnetic flux per pole, are the same for the three-phase as for the two-phase motor, and are slightly lower for the single-phase induction motor: the maximum output is the same for the three-phase as for the two-phase motor, and for the single-phase induction motor varies between about 35 and 45% of the maximum output of the same motor as polyphase induction motor. In other words, all polyphase induction motors have the same volt-ampere excitation, and same maximum output, while the single-phase induction motor at the same magnetic density has a slightly lower volt-ampere excitation and less than half the maximum output. The excitation of the single-phase motor is slightly lower, because one of the components of the magnetic flux is produced by transformation through the rotor, and therefore is lower by the drop of voltage in the transformation from the impressed energy phase of the stator to the magnetizing phase of the rotor.

The numerical values of reduction factors are, I believe, merely the average of the projections of the different coils as displaced in position from each other upon the main direction of the coil, or are the average cosine extending over an arc of 90 degrees in the two-phase motor or 60 degrees in the three-phase motor. I believe, however, that when the author speaks of three-phase winding, he refers to six-phase winding. The three-phase winding, which he refers to, is a winding arranged so that each phase covers an arc of one-sixth of a period, or one-sixth of the pitch of two poles; therefore all his conclusions, while they apply to such a six-phase winding, whether delta or ring, or Y- or star-connected do not apply to the real three-phase winding, where each phase covers an arc of 120° electrically, as used in synchronous converters and such machines. The two-phase winding would better be called four-phase, since it covers an arc of 90 degrees. Otherwise, however, the paper is very interesting, in giving a discussion of the effect of arc of distribution of the winding, as varying between 60 and 90 degrees.

R. E. Hellmund: Mr. Steinmetz says that there should be hardly any difference between two-phase and three-phase motors, but it is a fact that the leakage of the two-phase motor is considerably higher than that of the three-phase motor; and therefore it is natural that it is much more difficult to design a good two-phase motor than a good three-phase motor. The reasons for the difference in the leakage are various, but it seems to me that one of the main reasons is the following: the leakage consists of two kinds, one leakage going around each particular phase, and one leakage which is going to all three phases, going around the bunch of the three phases. Now, in the three-phase motors this given leakage is, for certain kinds of windings, practically zero, (*i.e.* the chiefly used diamond winding) since the vector sum of the three-phase currents is zero and that of the two-phase currents is a certain amount. I have made a series of tests which tend to show that this is one of the main reasons for the difference in the leakages.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

HEAT TESTS ON ALTERNATORS

BY SEBASTIAAN SENSTIUS.

Every electrical factory occasionally produces an alternator of a size that does not admit of a heat-test under normal conditions of operation, unless there happens to be another alternator of about the same capacity and voltage entering the testing floor at the same time.

In such a case the testing engineer has to resort to methods of tests which require a supply of energy approximately equal to the losses under normal operating conditions. Among those generally applied, Mr. B. A. Behrend's apparently is the simplest. It merely consists in short circuiting the stator winding and in opposing one half of the field winding to the other, each half being separately excited. The separate excitation makes it possible to limit the unbalanced flux to an amount sufficient to circulate the current through the stator winding. Numerous tests have proved that vibrations due to the unbalanced flux are practically harmless.†

It is unfortunate that the test just described may be applied only on alternators with more than eight poles, eight being the lowest limit. And since modern alternator design points towards the adoption of a few number of poles (turbo-alternators) it becomes imperative to find new ways of testing adapted to these cases.

The writer presents herewith a series of methods developed by him as substitutes for full-load heat-tests; they are all based on the assumption that the short-circuit test offers the data to predetermine in a sufficiently accurate way the regulation of an alternator, and also its normal field current and flux.

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†Trans. Int. El. Congress, St. Louis, 1904, page 528.

Referring to Fig. 1 and Fig. 2:

A. Calculated armature reaction in terms of the field current.
L. Induction drop, assumed to be constant for all power-factors.
R Resistance drop.
V. Terminal voltage.
E. Induced voltage.
F. Field excitation to generate E.
Fa. Actual field excitation cos ϕ – power-factor.

Under normal running conditions the temperature rise in the field coils is caused by the field current Fa. Barring from consideration the increased iron-loss in the armature teeth, caused by a distortion of the main flux by the transverse ampere-turns, we may say that the iron-loss under normal running conditions equals the loss produced by the flux excited by F amperes in the field coils. Now with most of the methods enumerated hereinafter to obtain normal losses in the stator copper, there will be no armature reaction involving an excitation with Fa amperes to obtain a flux corresponding to only F amperes on the no-load saturation curve.

Connection of the Field Coils: To overcome this difficulty the author has devised the following disposition for the field coils, Fig. 3.

Field coils of the same polarity are connected in series. Two sets of field coils are obtained thereby. Send through one set, f. i. s. s., the normal field current Fa, through the other set, $2F-Fa$ amperes. The average excitation corresponds to $(Fa+2F-Fa):2 = F$ amperes, producing the voltage E. The temperature rise is to be taken on the coils traversed by Fa amperes.

Now it is a question whether the complication of the field connections is justified by the results obtained. The author believes that the temperature rise can be gotten with almost as great accuracy by not changing the field connections, by sending F amperes through the coils, and multiplying the observed temperature rise by $\left(\frac{F\,a}{F}\right)^2$

Armature Coil Connections: The principle of the tests to be described consists in bringing current into the armature winding through two points between which no induced electromotive force has to be overcome. This suggests the use of either direct or alternating currents to obtain the normal heating in the stator winding.

Three kinds of windings are to be considered: The first is represented in Fig. 4a, a single-phase winding; every coil consists of turns of insulated parallel conductors, the ends of which are separately connected to the ends of parallel conductors of other coils.

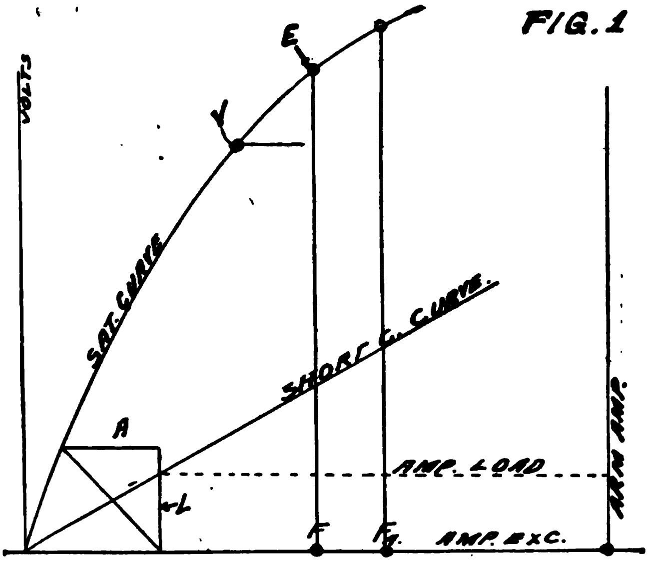


FIG. 1

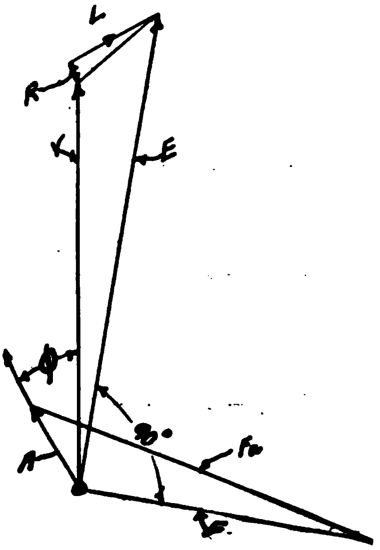


FIG. 2.

It is a question whether such a connection has ever been made, on account of the high cost of winding. However, its application to the first machine of a new size is justifiable, provided such machine is of a large current capacity and of a small

FIG. 3

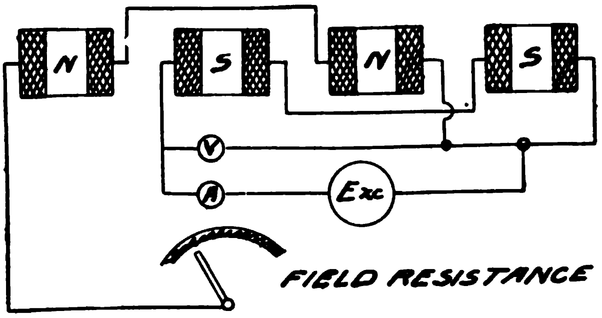


FIG 4a

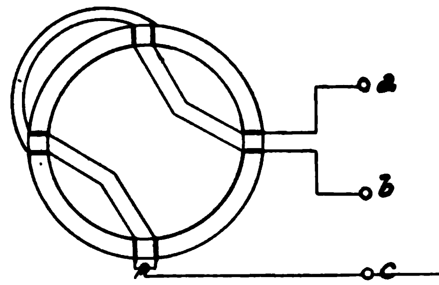


FIG 4b

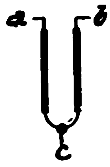
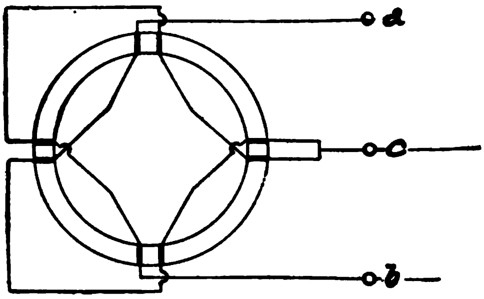


FIG 5



number of armature coils. To reduce the self-induced eddy-current losses, the heavy conductors of machines of large current capacity are subdivided into parallel insulated conductors. These, connected as indicated above, yield a winding which enables us to make a heat-test equivalent to a full-load test, simply by supplying an amount of energy equal to the full-load copper losses in the armature winding. The full-load current, either direct or alternating, enters the winding at the terminal *a* and leaves it at *b*. Now, since in each coil the direction of the current in one conductor is opposed to that in the other, the resultant magnetizing effect of the armature is nil. The fields being excited, the voltage can be measured between *a* or *b* and *c*. Diagrammatically, the connection is represented by Fig. 4b, which, suggesting a *U*, will be hereinafter referred to as the U-connection.

The next winding to be considered is the double-layer winding. Every double-layer winding can be transformed into a two-layer circuit winding (Fig. 5, circuits *a–c* and *b–c*) by opening one connection per phase. The current enters at *a* and leaves at *b*. The voltage is measured between *a* or *b* and *c*. Each slot will be found to have two equal volumes of current going in opposite directions. The magnetizing action of the current is nil, and thus this case is similar to that of Fig. 4a. For this reason the connection may also be referred to as the U-connection. Whereas on the one winding (Fig. 4a) the voltage applied on the terminals *a* and *b* is about the same for direct as for alternating current, on the other (Fig. 5) the direct-current voltage differs from the alternating-current voltage. We readily see that the resultant self-induced flux practically is zero in the slots; but it has its full value on the end connections (Fig. 5) so that the alternating-current voltage must be greater than the direct-current voltage for the same current intensity.

The third winding, a single-layer winding with turns of single conductors, is represented on Fig. 6. By loosening one connection per phase, this winding can be transformed into one shown in Fig. 7. The current enters the winding at *a* and leaves it at *b*. The voltage can be measured between either *a* or *b* and *c*. Diagrammatically, the connection is represented by Fig. 7b, and will be referred to as the Z-connection. It is immaterial whether direct or alternating current is employed; any current traversing the Z-connection produces a field shown in Fig. 8. Now, in the case of the direct current, the armature field is stationary with reference to the stator iron and causes an alternate weakening and strengthening of the revolving field poles. These fluctuations generate alternating electromotive forces in the field coils, and they might cause a breakdown of the field-coil insulation. The armature flux, stationary with respect to the armature iron, alternately faces a pole face and an inter-polar space; that is, two media of different magnetic conductivity. One consequence is a fluctuation of the armature

FIG 6

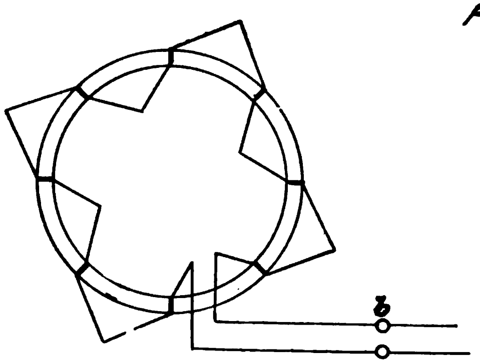


FIG. 7A

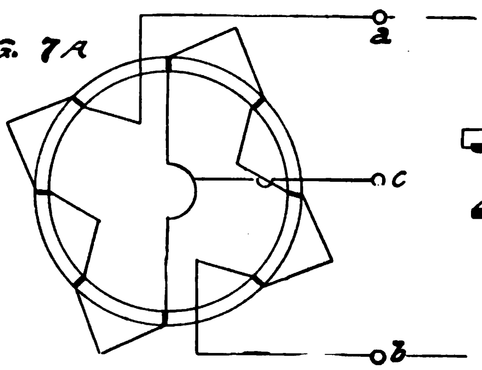


FIG. 7B

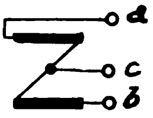
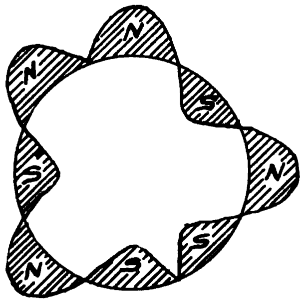


FIG. 8



flux, and a generation of alternating currents of double the frequency of rotation, short circuited on the commutator of the current-supplying dynamo. A second consequence is a fluctuation in the driving torque of the revolving field, which sets up vibrations in the whole structure. A third consequence is the generation of rather large eddy currents in the whole magnetic circuit, which increase the temperature rise above that of the alternator operating under normal conditions.

The originator of this test, Mr. R. Goldschmidt,* maintains, however, that the method has been tried with success on the testing floor of Messrs. Kolben & Co., Prague, Bohemia.

Entirely different phenomena are obtained by the use (in the Z-connection) of alternating currents of the frequency of rotation. The flux represented in Fig. 8 fluctuates in time-phase with the rotation of the rotor-field and causes a weakening of one half of the rotor field and a strengthening of the other half. By sending through the first half more excitation current than through the second half, it is possible absolutely to correct the unbalanced field.

A polyphase armature, the phases of which are independently Z-connected, and independently supplied with currents from a polyphase source, would generate a revolving flux constant in strength, stationary with respect to the rotor field, weakening one half of the latter and strengthening the other half. The field-weakening stator winding is a generator winding. The field-strengthening winding is a synchronous-motor winding. Because the ratio of resistance to the inductance of the windings is always very small, the current supplied will be in quadrature with the electromotive force of the source, and ψ being the phase difference between the latter and the alternator electromotive force, cos $(90-\psi)$ is the power-factor of the load of the generator winding. It is seen that any load with any power-factor can be secured with a Z-connected armature. For $\psi = 0$, cos $(90-\psi) = 0$, and the source of supply may be the generator itself, as will be shown farther on.

Reversing the functions of armature and field; that is, retaining the connections in Fig. 6, short circuiting the stator winding and bucking one half of the field coils against the other, yields the well known Behrend split-field test. In this case the resultant field remains unbalanced for an amount equal to that necessary to generate the electromotive force, which forces the current through the stator winding. With a Z-connected armature winding, and a pressure applied on its terminals *a* and *b*, the unbalance in the excitation current equals the current required to overcome the armature back-ampere-turns,

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*See E. T. Z. Heft 34, August 22, '01.

and it remains almost constant for a constant power-factor and for all voltages between *a* or *b* and *c*. For a power-factor equal to one the unbalance is zero.

With a split-field test, the unbalanced excitation current equals the sum of the currents required to excite the unbalanced flux, and to overcome the back-ampere-turns.

The great simplicity of the split-field test for zero power-factor load, due to the absence of a foreign source of the load, is also found in what the author would term the split-armature test. Referring to Fig. 7a, it consists in paralleling the armature coils by short circuiting *a b*, in retaining the usual field-coil connections, and, at last, in an unequal excitation of two halves of the rotor field. As in the split-field test, an unbalanced flux is required to circulate the current through the stator windings. Also, the unbalanced excitation current equals the sum of currents required to set up the unbalanced flux, and to compensate for the back-ampere-turns. It differs from the Mordey test in that the armature is split into halves. Applied on generators with a small number of poles, both split-tests have the disadvantage of producing on the generator side of the rotor field, a temperature rise greatly in excess of the rise under normal operation.

Loads with any power-factor may be obtained with a split rotor-field by connecting the terminals of the winding in Fig. 6, to a foreign source of current, the electromotive force of which has a definite phase relation to the electromotive force generated in the alternator under test. Any unbalanced flux can be annulled, and the unbalanced exciting current is limited to that required to make up for the back-ampere-turns.

As regards the iron losses, it is obvious that the split-armature test gives more accurate values than the split-field test, the smaller the number of poles.

TEST CONNECTIONS.

Figs. 9a and 9b, show the general connections of a U-connected single-phase alternator fed at equipotential points by the direct-current dynamo *D*. On Fig. 9b, the rotor has the normal connections to the exciter, whereas on Fig. 9a it is connected according to Fig. 3. *F F* are the dynamos and exciter fields; *R*, a rheostat; *A*, an ammeter; and *V*, a voltmeter.

Figs. 10a, 10b, and 10c, show the armature connections of a two-phase U-connected alternator fed by a direct-current dynamo *D*.

Figs. 11a, 11b, and 11c, show the connections of a U-connected Δ-wound alternator.

FIG. 9a

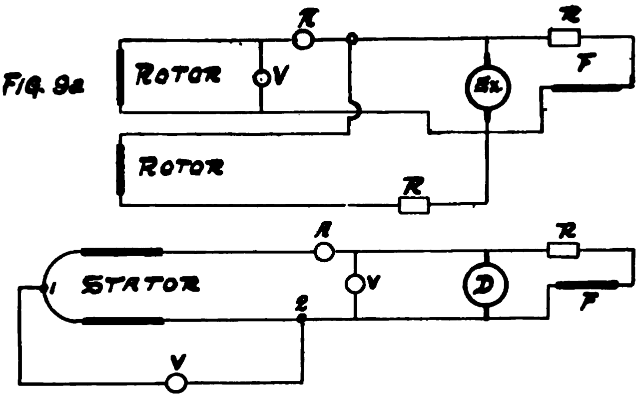
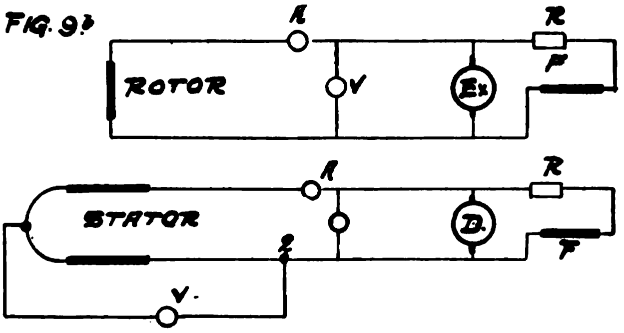


FIG. 9b



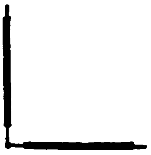


FIG. 10a.-

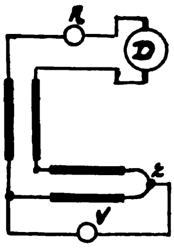


FIG. 10b

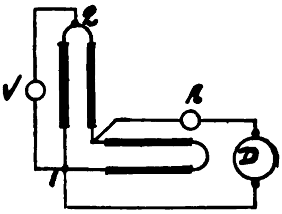


FIG. 10c

Figs. 12a, 12b, show the connections of a U-connected Y-wound alternator.

Next follow the connections to sources of alternating currents.

Fig. 13 represents the stator winding of a U-connected single-phase alternator, which derives its current from the secondary, *S*, of a transformer, the primary, *P*, of which is branched on the mains. *A* = an alternating-current ammeter and *V* an alternating-current voltmeter.

FIG. 11a.

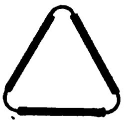


FIG. 11b.

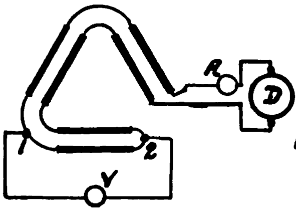


FIG. 11c.

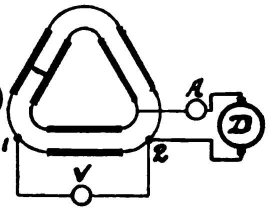


FIG. 12a.

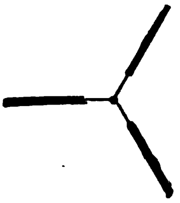


FIG. 12b.

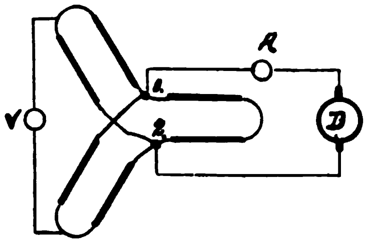
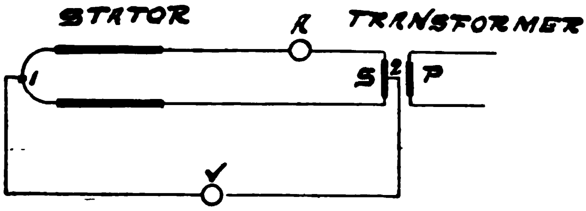


FIG. 13.



In Fig. 14, the primary derives its power from the stator windings working in parallel. It is connected to the points 1 and 2, the latter being a tap in the middle of the secondary *S*. The magnitude of the current in one leg on the U-winding then is

FIG. 14.

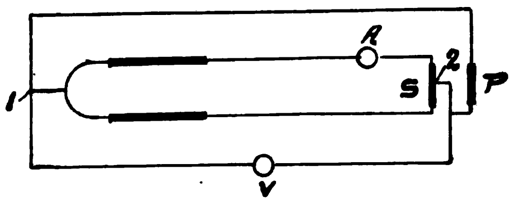


FIG. 15

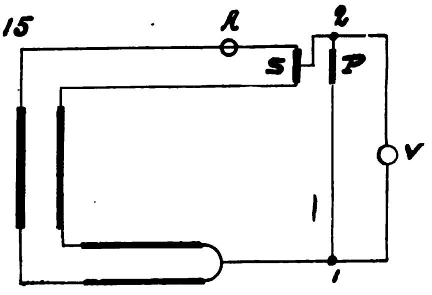
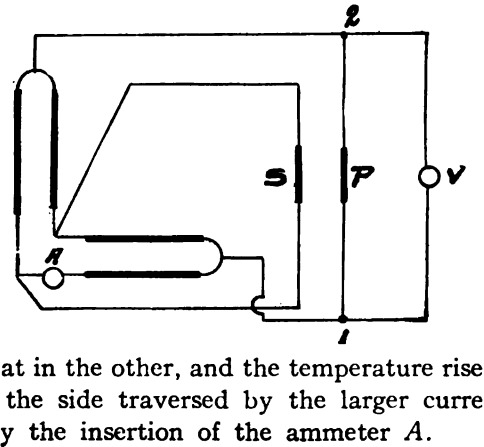


FIG. 16



different from that in the other, and the temperature rise should be observed on the side traversed by the larger current, the side indicated by the insertion of the ammeter *A*.

Figs. 15 and 16 show the same method of self-loading applied to a two-phase winding.

Fig. 17 illustrates the self-loading method applied to a single-phase Z-connected winding. The load necessarily is of zero power-factor, unless primary resistances are inserted in circuit.

Fig. 18 is the Behrend split-field test at zero power-factor with its simple connections. The unbalanced pull can be annulled by inserting in the winding circuit the secondary of a transformer, the primary of which is branched on terminals 1 and 2.

Fig. 17

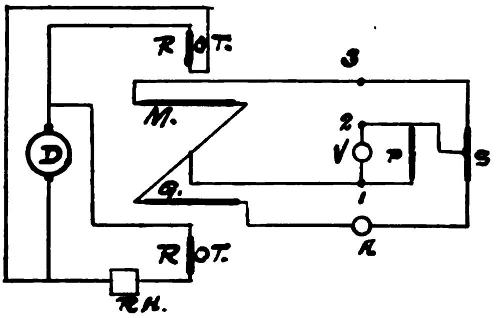


Fig. 18

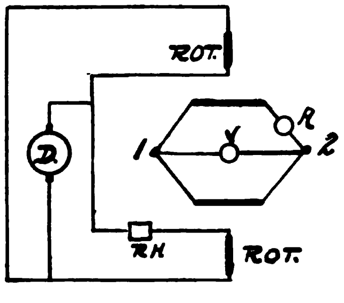


Fig. 19 shows the Mordey split-armature test as modified by the writer.

Concluding Remarks: The different connections for a heat-test treated above can be divided into three classes:

1. The test connections whereby no armature reaction is produced, represented by the U-connection. Full-load heat-tests can be closely imitated on machines of any number of poles, having the double-layer or parallel winding.

2. The split-field and split-armature test connections for

machines with a large number of poles and any kind of winding, whereby no foreign source of current is required, thus producing an unbalanced pull as explained above.

FIG. 19

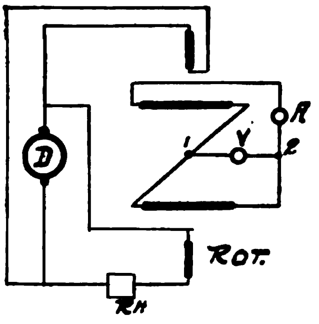


FIG. 20

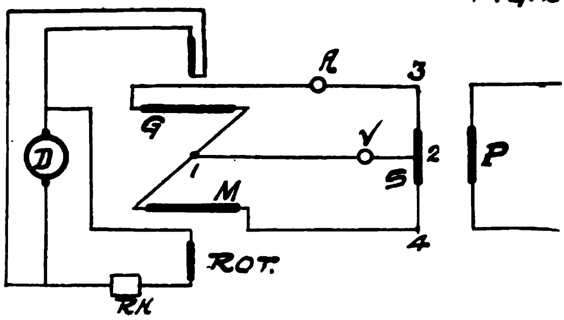
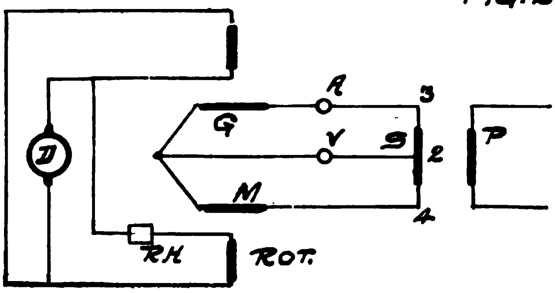


FIG. 21



3. The split-field and the split-armature test connections on machines with a rather large number of poles, whereby a foreign source of current is required, thus annulling the unbalanced pull as explained above.

The third class is interesting in that it offers the means to obtain the regulation curve of the alternator on any power-factor, and accurately to separate the drop due to self-induction in the armature from the drop due to back-ampere-turns. It also enables us to determine and to study the variation of the armature self-induction with different positions of the armature flux relatively to the revolving fields.

Referring to Figs. 20 (split-armature) and 21 (split-field), which are the test connections spoken of above, the voltage across the secondary *S* is always equal and opposite to the impedance voltage of the stator winding.

It may be in any phase relation to the generated voltage, depending upon the phase difference between the generator voltage and the voltage impressed on the primary of the feeding transformer.

The variation of armature self-induction (equal to the secondary voltage) with the position of the armature flux can thus be studied by keeping the current constant, and varying the phase angles between the alternator and the transformer voltage.

The voltage measured between 1 and 2 always equals the voltage induced in both the generator and motor windings.

G, being the generator side, the voltage across (1–3) is the generator terminal voltage and that across (1–4) the motor terminal voltage, (1–3) being smaller than (1–4). Whenever the fields are balanced, the regulation curve is obtained by plotting the curve representing the voltage (1–3) as a function of the generator field-current.

The author does not believe it necessary to explain in detail how the test connections for polyphase alternators are made. It is sufficient to say that a polyphase source has to feed the stator winding.

APPENDIX.

Since writing this article my attention has been called to a series of test connections in chapter VIII of "Alternating Currents and Alternating Current Machinery" by D. C. and J. P. Jackson, which contains a résumé of a paper on "Testing and Working Alternators" read by W. Mordey and discussed by Prof. Ayrton.*

The authors' conclusions are:

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*Journal Inst. E. E., Vol. 22, pp. 116 and 136.

1. The split-armature connection for heat tests (Fig. 19) is disclosed in Mr. Mordey's paper.

2. The split-field connection for heat tests (Fig. 18) was proposed by Prof. Ayrton in the course of his discussion.

3. The method of obtaining the regulation for zero power-factor load by means of a split-field connection (Fig. 18), was devised by Mr. Behrend.

DISCUSSION ON " HEAT-TESTS ON ALTERNATORS "AT MILWAUKEE, WIS., MAY 28, 1906.

C. P. Steinmetz: This paper is very interesting, as it deals with a problem of machine testing and manufacture that is becoming more and more serious, and will probably in the future be a proper subject of investigation by our standardizing committee. The investigation and measurement of the temperature-rise of a machine under load have been made by loading the machine to full load, and then running it a sufficiently long time to reach stationary temperature. The size and number of machines has increased so fast that even by relegating these heat-tests to the night time, when not much power is used for operating the factory, the amount of power required to make the tests exceeds that available. With the development of hugh alternators in the last few years, the amount of power required by a single alternator has risen beyond the available power of most manufacturing plants; it is not very uncommon now to find two or three alternators in a factory, of sizes varying from 5 000 to 8 000 kw., waiting to be tested. With such hugh machines, the time required to reach stationary temperature is from 20 to 24 hours, or more. Few facilities are available now really to make a full-load heat-test of these machines; therefore it has become necessary to determine the heating at full load without being required to put full load on the machine.

A number of methods have been produced and recommended, none of them being really quite satisfactory. The split-field method, the split-armature method, and the method so ably discussed in the paper—all are steps in this direction. A simple compromise method has been used for a number of years. This consists in making a no-load open-circuit test, and a no-load short-circuit test; that is, running the machine at open circuit at over normal voltage a certain length of time, whereby the core losses and no-load losses are more than normal; and then running the machine at short-circuit on overload current for a certain number of hours, whereby the load losses are more than normal, and from the heating observed under these two conditions, estimate the actual rise of temperature at full load. These tests are very satisfactory as check tests; that is, to determine whether the rise of temperature of the machine is what it was expected to be. But they really beg the question; because they do not show how much overload in voltage and overload in current is required to represent full load in both applied simultaneously. This means that a machine must be tested first at regular full load, observing the temperature rise; and then by experiment find out how much excess voltage, how much excess current, successively applied, give the same rise of temperature. Then by exercising judgment all the other machines of the same size, type, and character can be tested by comparing the open-circuit and the short-circuit tests. But the first machine must still be tested at full load, and that is not feasible; it is one of the difficulties met with in attempting to make full-load tests with large machines.

The other difficulty is that even if there were unlimited power at ones disposal, if one were able to run a 5 000- or 8 000-kw. alternator in the factory at full load for 24 to 36 hours, the full-load temperature rise would not be got, because so long a time has elapsed before the machine temperature has become constant, that it is practically impossible to maintain constant air temperature; and the variation of air temperature must be reckoned with. If the air temperature changes during the test, it is not right to call the temperature rise the difference between the machine temperature and the air temperature at the moment of shutting down; nor is it right to compare it with the air temperature in starting up, nor with any intermediate temperature. The problem is not merely to be able to run the machine at constant full load for a considerable time, but to keep the air temperature in a room large enough to accommodate a 5 000- or 8 000-kw. alternator constant within a degree or two during the whole length of time. The problem is so formidable that the solution is rather difficult. Theoretically one may say it could be done by running the machine at full load for some weeks, and recording continuously by registering instruments the temperature of all parts of the machine and of the air; then, after discarding the records of the first 24 or 48 hours, compare the average temperature of the machine with the average temperature of the air, averaging over a considerable period so as to offset the daily fluctuations of temperature. This method is not practicable in the factory.

Hence it is a very difficult problem to determine the temperature rise of a very large machine under full load and service conditions. Even if by some compromise we should be able to run the machine without power expenditure with such internal losses as would represent the full-load losses—still the other problem would have to be solved, to correct for the variations of the air temperature. Not only must the load on the machine be kept constant, but constant, too, must be kept the air temperature of the surrounding space; this is almost impossible

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28–31, 1906.

DIRECT-CURRENT MOTOR DESIGN AS INFLUENCED BY THE USE OF THE INTER-POLE.

BY C. H. BEDELL.

The advent of the inter-pole is due to the demand for motors which operate under conditions so severe that perfect results can not be obtained with those of the standard design. The machine-tool builders quickly saw the advantages of the individual motor drive, largely on account of the possibility of obtaining speed variations, but the 33% increase in speed which the standard constant-speed motor would allow was not sufficient for their requirements. As it seemed evident that the motor builders could furnish motors of special design that would satisfy almost any demand they might make in the way of speed changes, the tool builders have adapted their machines to this form of drive, and call for motors that will operate at from 100% to 500% above minimum speed.

The design referred to as " standard " is that of the usual type, having no series winding to control the field distribution. In designing motors along standard lines to fill such speed specifications, the greatest difficulty is to overcome the sparking tendency. As the minimum speed is very low, the armature must have a large number of turns. It therefore follows that the self-induction of each armature coil is quite high, so high that the qualities of the carbon brush are not sufficient to prevent sparking as the short-circuited coil passes out from under the brush. No assistance can be obtained from the fringe of the main field at the high speed, for the field is then so weakened that the armature reaction reduces the fringe approximately to zero.

The attempt has been made to modify the proportions of the motor so as to reduce this sparking tendency; that is, by making the armature very weak, and the field very strong. Such changes, however, are only a help; they do not cure the trouble, and in addition the machine is very large for its output. Even with such changes in the proportions of the machine, the qualities of the carbon brush are depended upon to control the sparking. That no fringe is available to assist in this control, is shown in Fig. 1. The two curves there shown were made from readings taken by means of exploring brushes around the commutator of a commercial machine of standard design,

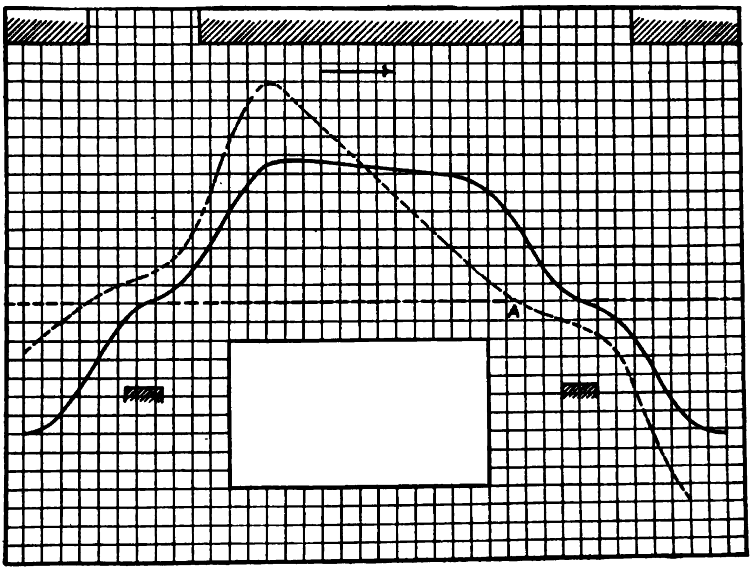


FIG. 1.—Field distribution curves of 3-h.p. 275-1100 rev. per min. motor of standard design. Curves taken at high speed.

having a weak armature and powerful field at minimum speed, with an air-gap of good size. Both curves were taken with the armature running at high speed, the one with solid line being the no-load curve and that with the broken line being the full-load curve. Even at no load, considerable armature reaction is shown, due to the fact that the field is so extremely weak. The full-load curve shows the heavy armature reaction of this type of machine, a reaction in itself not objectionable except as it influences the sparking condition. This full-load curve illustrates the point mentioned above, that at high speeds no assistance can be had from the fringe of the main field in the control of the sparking. At the point *A* the curve crosses the zero line. This point is under the pole corner, and shows that here the main field is just balanced by the ampere-turns on the armature; that is, by the armature field. It follows therefore that no amount of shifting of the brushes will help the commutation, for by moving the brushes back, this point *A* will also move back. The presence of the armature field is shown by the line to the right of the point *A* being below the zero line. At the brush position the distance between these two lines is considerable, and illustrates the intensity of the armature field.

It is thus shown that not only has the short-circuited coil no fringe from the main field to assist the reversal of the current, but it is cutting the lines of force of the armature field in the direction to maintain the current in the coil. The result is that there is a sudden change in the current strength as the coil passes out from under the brush, resulting in continuous sparking. At speeds below the maximum the fringe of the main field may be used to assist in the commutation, but with a given setting of the brushes, correct conditions can be obtained for one load only, as on light loads the fringe is too powerful, and on heavy loads the fringe is too weak. The motor when thus used is not reversible.

To obtain perfect commutation, a variable-speed motor should be free from all these defects; that is, it should be so constructed that a heavy commutating field is provided to assist in the reversal of the current in the short-circuited coil, and that this field should vary with the load. It follows therefore that the commutating field must be independent of the main field.

Having in mind the weak points of the standard motors, when applied to variable speed work, the inter-pole motor was designed, with results so satisfactory both as regards sparking and on account of the reduction in size made possible, that the motor is not only used for variable-speed work, but also for constant-speed conditions.

As it is necessary that the commutating field be independent of the main pole, small auxiliary poles called inter-poles are used, placed midway between the main poles, with pole faces covering the region of commutation. In order that the proper commutating field may be obtained that would vary with the load, the inter-poles are wound with the necessary number of turns and connected in series with the armature. Thus when the load on the armature is heavy, the ampere-turns on the inter-poles are large, resulting in a powerful commutating field; and when the armature load is light, the excitation of the inter-poles is light, resulting in a weak commutating field. That is, by this construction a heavy commutating field is provided when required, independent of the main field strength, and this commutating field varies with the load until the saturation point of the core of the inter-pole is reached. In the actual

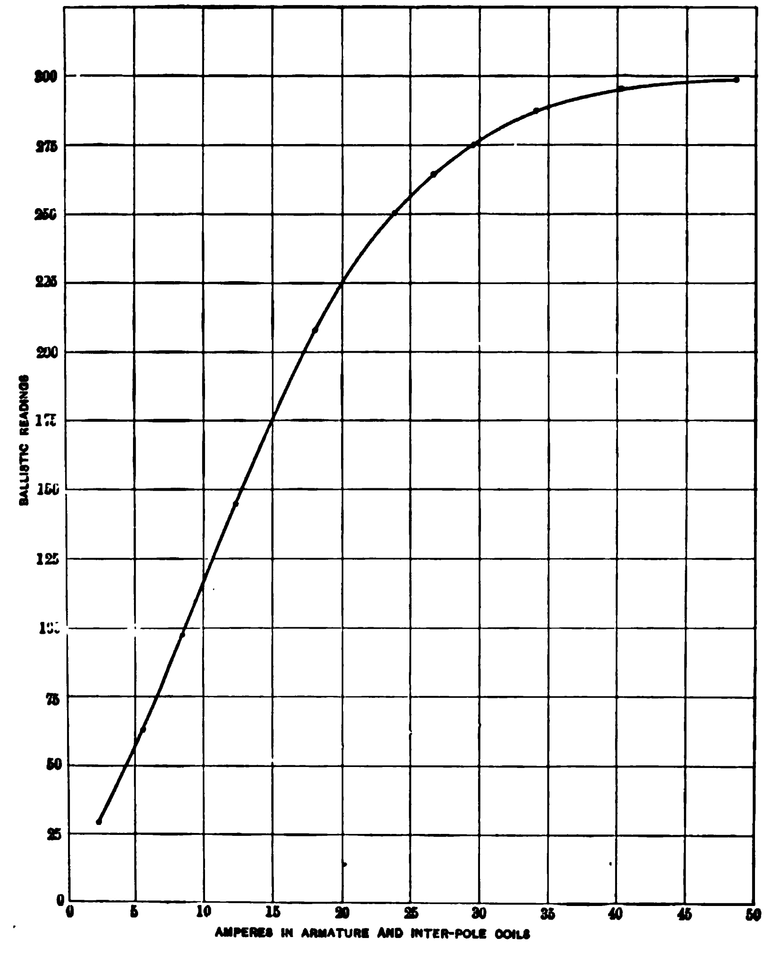


Fig. 2.—Saturation curve of inter-pole core.

motor this saturation point is at about 100% overload, well beyond the point of proper operation of the motor. This is shown by the curve illustrated in Fig. 2. The readings for this curve were made with a ballistic galvanometer and exploring coil. The motor was a 5 h.p. 220-volt, 20-ampere machine. In making the test, the armature was clamped so that it could not turn with brushes placed in their proper commutating position and current was sent through the armature and inter-pole coils. No current was used in the shunt coils. The exploring coil consisted of a few turns of fine wire, placed between two sheets of mica. In taking a reading the exploring coil was placed in the air-gap between the inter-pole and the armature, current was thrown on the armature and inter-pole coils, and then by a quick movement the exploring coil was withdrawn, thus producing a kick in the galvanometer. Successive readings were taken at different current strengths, and the results plotted as shown.

The general arrangement of the different poles is shown in Fig. 3.

In the case of the standard motor, where the fringe of the main pole is made use of for commutating purposes, the brushes have to be shifted if the direction of rotation is to be changed. Where the inter-poles are used, the commutation takes place under the middle of the inter-pole face, that is, on the neutral line. As the winding of the inter-pole is permanently connected in series with the armature, the reversal of the current in that circuit necessary to change the direction of rotation, reverses the polarity of the inter-poles, thus giving the necessary change in the polarity of the commutating field without any shifting of the brushes. The motor is therefore perfectly reversible. The ampere-turns on the inter-poles are considerably greater in number than those on the armature, since not only is it necessary to neutralize the armature fields, but also a field must be produced for commutating purposes. It will thus be seen that no matter in which direction the current may flow, the inter-poles are always more powerful than the armature, and the commutating field is always in the right direction, and of the proper strength. The machine may therefore be operated as a motor with rotation in either direction, or as a generator, without shifting of the brushes, or change in the connection between the armature and inter-pole coils.

It may be thought that as we are not dealing with a straight line in the saturation curve of the inter-pole, that the commutating field would not be sufficiently close to being proportional to the load on the armature. Fortunately the qualities of the carbon brush allow of quite a wide variation from exact proportionality, and the motors operate at maximum speed without sparking with any load up to the saturation point of the inter-poles.

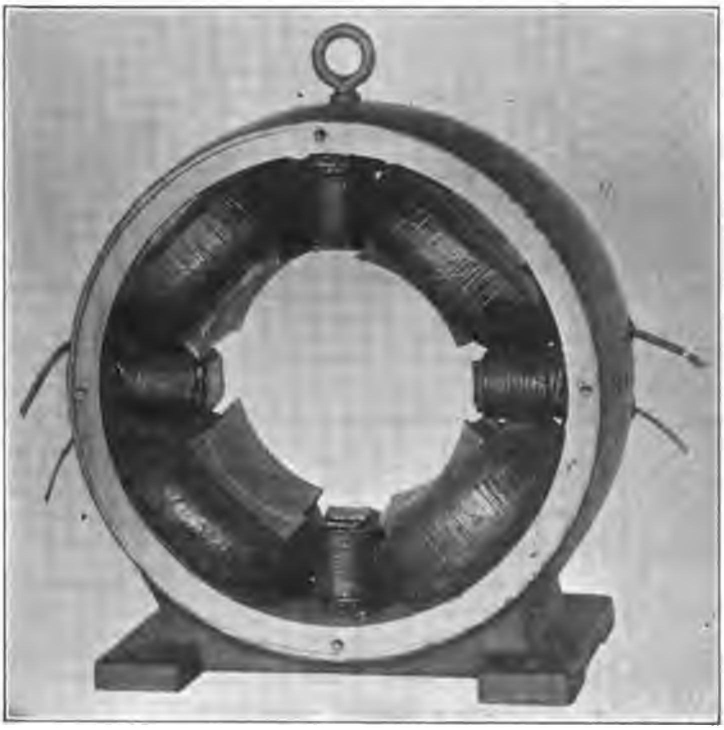


FIG. 3.—General arrangement of poles of inter-pole motor.

The question may be asked whether the same excitation is required on the inter-poles for a given load, for both high and low speeds. Experiment has proved conclusively that if the excitation of the inter-poles is correct for high speeds, it is also correct for all lower speeds. Although the same number of lines of force are sent into the armature from an inter-pole for a given load, irrespective of the rate of rotation, yet the electromotive force generated in the short-circuited coil is proportional to the rate of rotation. Thus a high electromotive force is provided for the very quick reversal of the current at high speed, and a much lower electromotive force is provided for the slower reversal at the low speed.

As a general illustration of the reactions which take place in the field distribution of a motor, both without and with inter-poles, the sketches Figs. 4, 5, 6, and 7, are given. Fig. 4 represents the field distribution of a constant-speed motor running under no load, having a uniform field distribution over the pole face. When load is thrown on the armature, the reaction weakens the field under one pole corner, and strengthens it under the other corner. Also an armature field is produced in the space between the main poles. These effects are illustrated in Fig. 5. If now the main field is weakened to produce higher speeds, the armature reaction under the same load is greater, weakening one pole corner so that the field may be reduced to zero, as illustrated in Fig. 6. It is evident that under such conditions the shifting of the brushes back will not help the commutation, as there is no field under the pole corner to help reverse the current in the short-circuited coil. The operation of the motor when fitted with inter-poles is illustrated in Fig. 7. The current from the line to the armature

FIG. 4. FIG. 5.

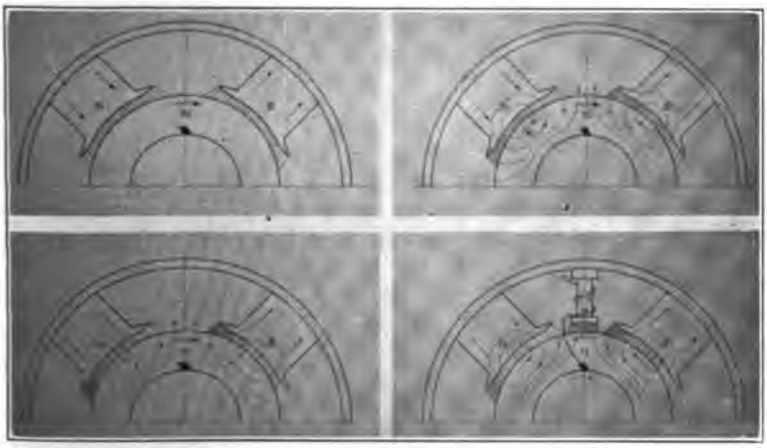


FIG. 6. FIG. 7.

Sketches illustrating field distribution under different conditions.

passes through the coils on the inter-poles. As these coils have more turns than the armature, they overpower the armature field and produce the proper field for commutation,—powerful or weak, in proportion to the load on the armature. This commutating field being independent of the main field, can be made to control the sparking tendency, no matter how extreme the reaction may be over the main pole face.

In order to show the exact field distribution of an inter-pole motor, readings were taken by means of exploring brushes and a voltmeter around the commutator of a 5 h.p. 275-1 100 rev. per min. motor both at low and high speeds. The low-speed curves are shown in Fig. 8 and those for high speed in Fig. 9. In each case the solid line is the no load curve, and the broken line the full-load curve. The positions of the main and inter-poles, also the brushes, are shown by the shaded portions. In the test at low speed, very little armature reaction is shown. At high speed the reaction is very heavy, so much so that the polarity of the weakened pole corner is not only reduced to zero, but is reversed to quite an extent. The curve however

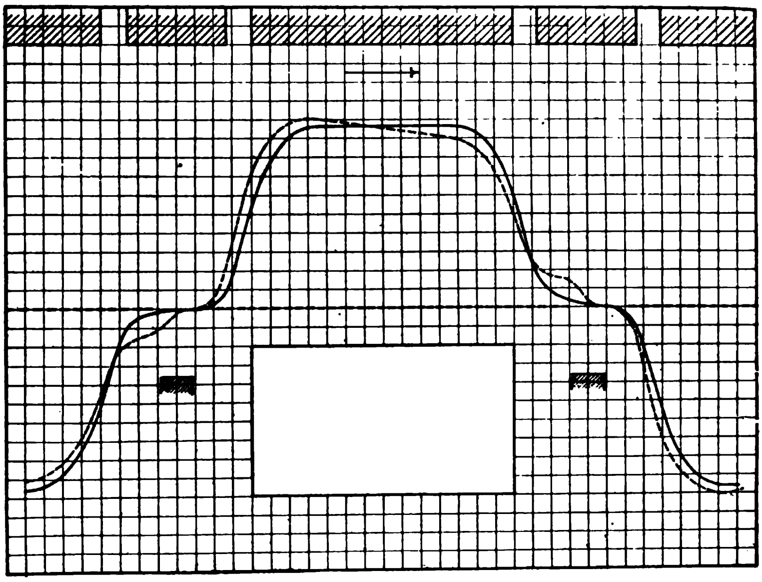


FIG. 8.—Field distribution curves of inter-pole motor, 5 h.p,, 275—1100 rev. per min. curves taken at low speed.

is brought back to the proper side of the zero line by the inter-pole, and sufficient field is shown to give proper commutation. In tests of this kind the voltmeter readings are proportional to the intensity of the field in the portion under test, except in the immediate neighborhood of the brush. The electromotive force of self induction of the short-circuited coil due to the current being reversed in the coil at that point, prevents the apparent voltage as given by the exploring brushes from being proportional to the magnetic field. The two electromotive forces thus generated, oppose each other and as a result there is a depression in the curve at that point. It is probable the field is practically uniform over the inter-pole face.

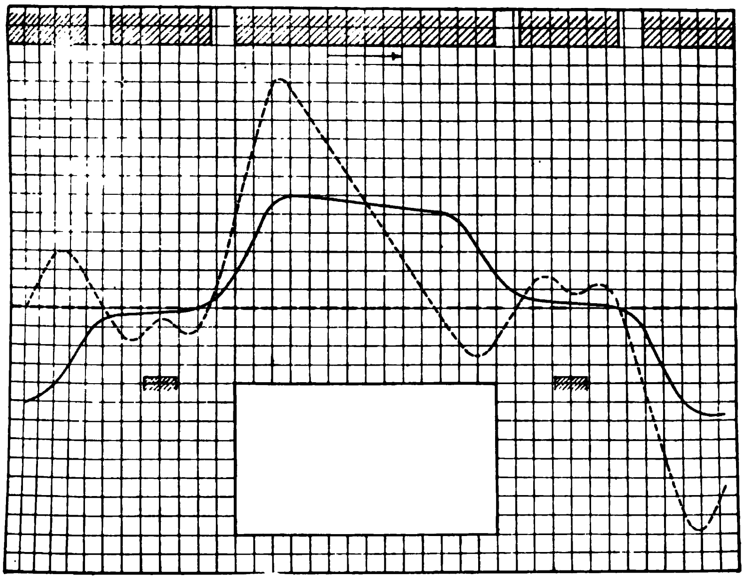


FIG. 9.—Field distribution curves of inter-pole motor, 5 h.p., 275-1100 rev. per min. curves taken at high speed.

When the fringe of the main field is used for commutating purposes, it is necessary to bevel off the edge of the pole, so that the fringe shall be sufficiently wide. In cases where the teeth of the armature are wide, it is necessary to make the bevel of the edge of the pole quite wide. This robs the pole of valuable area, tending to increase the speed of the motor. With the inter-pole construction, as the fringe of the main field is not used for commutating purposes, the beveling or skewing of the edge of the pole may be much narrower, and therefore the effective pole area is larger. If it were not for the humming of the armature teeth, the main pole could be rectilinear, and without bevel. If a skew form is used, it should amount to about one tooth and slot of the armature, this being sufficient to dampen all tendency to vibration of the teeth.

The inter-pole produces a much better form of commutating field than can be obtained from the fringe of the main field, even on constant speed motors, unless an extremely wide bevel is used. This is due to the fact that the inter-pole may be made much wider than the bevel of the main pole, thus furnishing a broad uniform field, well suited to commutating conditions. The current is therefore quite uniformly distributed over the brush face, and none of the difficulties such as pitting or incandescent positions of the brush, due to too narrow a commutating fringe, are experienced.

In the designing of machines along the old lines, some of the dimensions are limited by the sparking condition. For example, it will not do to put more than a certain number of ampere-turns per inch of periphery on the armature, as a larger number produces too great armature reaction. Similarly it will not answer to have too small an air-gap for the same reason. With the inter-pole construction these conditions do not pertain, for no matter what the armature reaction may be over the face of the main pole, the inter-pole always gives the proper field for commutation. It follows therefore that radical changes in proportions may be made, materially reducing the size of the machine.

The change in the relative amount of iron and copper in the armature, makes quite a change in the form of the efficiency curve. As the amount of iron is less, the hysteresis and eddy current losses are less. The increased amount of copper makes $I^2 R$ armature loss greater. The full load efficiency is practically the same as in the standard motor, but on light loads the efficiency is increased. The motors therefore show a much better efficiency under varying load approaching the condition of the all day efficiency of the transformer.

In this paper the subject has been treated in connection with motor design, but the advantages of the inter-pole pertain equally well to generator conditions. By the use of the inter-pole the following advantages are obtained:

A powerful commutating field is provided to assist the carbon in resisting the sparking tendency, and this field is independent of the main field.

The intensity of the commutating field is proportional to the load on the armature

The brushes are placed on the neutral line, and in consequence the machine is perfectly reversible, and may operate either as a motor or dynamo, without shifting the brushes or changing any of the connections.

A large number of ampere turns per inch of periphery is permissible, also small air gaps, resulting in a large output for the material used.

The form of the efficiency curve is better suited to the average load.

DISCUSSION ON "DIRECT-CURRENT MOTOR DESIGN AS INFLUENCED BY THE INTER-POLE," AT MILWAUKEE, WIS., MAY 28, 1906.

H. F. T. Erben: About fourteen or fifteen years ago I was interested in trying the effect of commutating the poles of a 500-kw. machine. The results were not satisfactory. In looking over the old data, I see now how close we came to attaining success: the pole was properly proportioned, but we did not provide a sufficiently large magnetizing force for the commutating field. We then turned our attention to other matters, and did not renew our experiments on this kind of motor until two or three years ago, when the need of motors for machine-tool work, and generators for direct connection to high-speed steam-turbines, made it necessary to take up again the developing of the commutating-pole machine.

Our experience during the last two years in developing machines of all sizes, even as large as 2000 kw., has proved the value of the commutating-pole machine to all designers of commutating apparatus. We have considered carefully the shape of pole, length of air-gap, magnetizing force, and so forth. About eighteen months ago we attempted to take the curves of a small experimental machine by the method outlined by Mr. Bedell; we got a satisfactory curve at the portion between the brushes, but at the point where we wished to determine the magnetic distribution the curve was obliterated, due to the coils being short-circuited by the brushes. We wound on an experimental coil which had the same pitch as the armature coils; we then connected it to the two collector rings and to the oscillograph.

The possibility of the curve being flat, as mentioned by Mr. Bedell, is realized in certain cases. The curve is flat, or nearly so, except when the machine is operated with a very weak field; then it becomes slightly tilted; but there is no dip in it, as some suppose. We have found that the flux as plotted by the oscillograph curves is practically proportional to the load on the machine.

A description of a generator recently built by the Siemens Company in England says that the generator has a separate and distinct structure for the commutating circuit; that is, the main magnetic yoke is not depended on for carrying the flux.

On high-speed generators fitted with commutating poles and direct-connected to a steam-turbine running at from 1800 to 2000 rev. per min., we find the commutation excellent and the regulation very fine. One machine, a 2000-kw. direct-current generator, direct-connected to a steam-turbine, running at 750 rev. per min., is practically flat-compounded without a series field; it is done by giving the brushes a slight shift backward.

To show the close regulation obtained on a 50-kw. machine with the brushes directly on the neutral point, I would say that the pressure between no load and full load varied practically from 510 to 500; with exactly the same position of brush and a weakened field, the drop in voltage was from 400 to 384. By giving the brushes a slightly backward shift the machine would over-compound 10% before the limit of sparking was reached; in other words, the machine had a wide range of commutation.

I have also found that commutating poles are entirely satisfactory on machines of large ampere capacity. On some 7000-ampere machines recently built, with a range of voltage of from 60 to 140, the load was carried throughout the whole range without a sign of sparking.

Will Mr. Bedell please say what proportion he found on motors between the armature reaction from brush to brush as compared with the magnetization of the poles?

C. H. Bedell: The proportion of the turns on the armature of the pole were largely air-gap, not the U-pole; but as a general thing on machines from one to fifty horse power, variable-speed motors, 4 to 1, the increase in ampere-turns on the inter-pole was abou 30%.

H. F. T. Erben: That agrees with my experience and the experience of French and German builders. They have found that it is not possible to use a small air-gap on a large machine; doing so produces unstable results and a certain amount of sparking. With the proper air-gap for commutation, the ratio is 1.2 to 1.35.

I have seen in a number of German papers and other foreign publications, poles of odd shapes, some tilted one way, some another; some with a triangular cross-section; and others had holes drilled in one edge. We tried these schemes but could not obtain any improvement in the commutation.

W. L. Waters: The introduction of auxiliary commutating poles in direct-current machines was first proposed about 15 years ago; but no use was made of this method of assisting commutation until quite recently, the reason being that the commercial requirements of direct-current designing did not require any auxiliary aids to commutation. The direct-current machines that were built 10 years ago were built economically and made to operate satisfactorily without auxiliary poles. There was no market for the auxiliary-pole machine until the demand arose for variable-speed motors and high-speed generators.

The demand for a direct-current motor capable of considerable speed variation practically originated with the multiple-voltage system. This system demonstrated that there was a good market for individual motors for driving machine tools. Although it has not yet been decided whether the individual motor drive is the most economical system for a machine shop, a demand has arisen for shunt-wound direct-current motors whose speed can be varied about 3 or 4 to 1. The only way in which such a motor can be economically and commercially built at the present time is by using an interpolar construction.

High-speed generator construction practically dates from the construction of the steam-turbine, and the steam-turbine has been in commercial use only a few years. The fact that generators are running satisfactorily at the high speeds at which steam-turbines operate has accustomed operating engineers to high-speed electrical machinery. The result of this is a demand for higher speed motor-generator sets and synchronous converters, the assumption being that such sets cost less and require less floor space. Motor-generators and synchronous converters are now built to run at nearly twice the speed that was thought practicable two years ago, and it seems as if the tendency were toward still higher speeds.

The main development in the next few years in direct-current machinery will probably be in connection with the extended use of the auxiliary commutating pole. The commercial success of this construction for variable-speed motors has already been demonstrated, and it is probable that the auxiliary will be used extensively in high-speed generators, reversible boosters, and similar machines which operate under severe commutating conditions. Almost every direct-current designer at the present time is investigating the possibilities of this auxiliary commutating pole. At present very little is known of its effect on commutation, with what have heretofore been regarded as prohibitive reactance voltages. It will be interesting to find out just what its limits are in this direction, and to what extent it will reduce the cost of direct-current machinery.

N. J. Neall: What effect will the inter-pole have on the design of large capacity motors carrying heavy currents? and to what degree will the requirements for ventilation be affected as compared with present standard motors?

C. H. Bedell: On the small machines—up to 50 h.p., 4 to 1, which have been built—the proportions have been modified so as to offset the extra cost of the inter-poles; that is, the air-gaps on the main poles are as a rule smaller than in the normal machine, for the reason that the sparking is controlled independently of the armature reaction. By making the air-gaps smaller, the necessary field excitation is reduced and the field diameters kept down. The inter-poles themselves are not very large. At the present time there are in use the same number of inter-poles as main poles; these inter-poles are about half the length of the armature core, so that they do not interfere very much with the circulation of air. The usual temperatures of the machine are within the specifications of the Institute.

S. Senstius: Will Mr. Erben kindly explain the application of the inter-pole on turbo-generators? As I understand it, one of the difficulties in the design of these generators is to get rid of the heat produced by the core losses; the core losses are said to be very great. Now in order to reduce the core losses you have to reduce the flux; you also have to reduce the number of poles to keep down the frequency, and the armature ampere-turns per pole become very great. The induction in the teeth under the main poles being made very small, it seems to me that the iron losses may be very small at no load; at full load, however, the main field is very much distorted by the large transverse m.m.f., and sometimes the maximum induction in the teeth under the leading poletips becomes twice as great at full load as it is at no load. Thus it seems to me that in such cases it would be necessary to compensate the armature transverse turns by a winding on the pole faces.

H. F. T. Erben: Machines have been built with both a distributed winding and the so-called Deri winding, however somewhat modified in that it had a commutating tooth. There has also been built a machine which had no distributed winding, only a plain commutating coil being used. The latter type of machine has low core losses and the heating is very conservative. A 500-kw. direct-current vertical turbine-generator set of this type has an efficiency of 96%. The maximum temperature rise of this machine is about 40° Cent. The armature is artificially cooled by a downward draft of air set up by means of fans attached to the lower end of the armature. The armature losses represent about 1.4 watts per square inch. The draft suffices to keep it cool.

N. J. Neall: What effect would an inter-pole have on series railway motor design, and what is its value?

C. H. Bedell: That opens up a pretty big field, and we are at present designing motors along that line. We have made some very satisfactory experiments. I think one of our standard machines 500 volts, 10 h.p., 4 to 1 variable-speed motors —could not be made to spark with 100% overload, and with but 9% field excitation. The point was to find out if with that method of construction—of course, the machine was not designed for that class of work, it was not of a shape suitable for railway purposes, but was one of our standard machines—we could use that method for railway motor work so as to obtain some additional economical speed points, other than the two speed points in the series parallel control. The experiments were thoroughly satisfactory: not only would the motor not spark, but we got a wide range of speeds.

The use of inter-poles makes quite a little difference in the size of the machine, because we can use much deeper slots than in the ordinary construction, on account of not being hampered by the armature reaction; I think, therefore, railway motors could be made that would give three or four extra running speeds, maybe double the speed of the ordinary motor, without any difference in size. The shunting of the current off the series field would reduce the field, and in laying out a machine for that class of work, of course the armature wire would have to be large enough to allow for the extra current, and that could probably be done by using a little deeper armature slot. The result of heating, then, would be no greater than in the present case, with no difficulty in respect to field heating, and several speed points with high economy would be obtained.

President Wheeler: In dynamo designing the inter-pole is undoubtedly a desirable feature; but in motors for variable speed, while I consider the inter-pole an excellent device, I believe that it is practically on an equality with several other means for obtaining variable speed, when the entire cost of the equipment is considered.

There are, of course, several ways of varying the speed of a direct-current motor. When the total cost of the application, including that of the driven machinery, is considered, I think the cost of a field-weakening motor, which is the one in which the inter-pole is employed, will be as great, if not greater, than the cost when the speed variations are obtained in other ways, such as by the use of multiple voltages, provided equal ranges of speed are obtained. I am somewhat of a believer in multiple voltage as the best method of obtaining speed variations. I am aware that this method is opposed by machine-tool builders, but time will show whether they will give up that opposition or not. Machine-tool builders began with opposition to motors in any way and in any form, but they have changed front on this question and in time I think they may give up some of their present opposition to the necessary four wires. In cases where machines are to be used in reasonable quantity, it seems to me that the four-wire or multiple-voltage method is much simpler and far less expensive in first cost. Of course where tools are not to be used close together, the advantages in favor of some other method of speed variation are obvious. The circumstances of each particular case should be considered.

David Hall: The author says that inter-pole motors are used not only for variable-speed work, but are also found useful for constant-speed conditions. I think that the inter-pole has given rise to a condition where the engineer can show his discretion as to the proper place in which to use it. If a machine can be built which is limited in design only by heating, and not by commutation, I think it is only an unnecessary complication to introduce inter-poles or any other auxiliary device that assists commutation. For instance, if the problem were to design an ordinary 30-h.p. 200-volt, 600-rev. per min. motor, the designer would find no use for auxiliary devices for commutation, because 100% overload could be carried on the motor without difficulty, and the output limited, not by sparking, but by heating. On the other hand, when the problem is to design a machine to give 4 to 1 speed variations, and it cannot be done without some auxiliary device, then the necessary means should be used for producing a satisfactory machine to accomplish that end. The author says:

> Experiment has proved conclusively that if the excitation of the interpoles is correct for high speeds, it is also correct for all lower speeds.

I have found that there is a much greater range at low speeds than there is at high speeds. In a number of experiments carried on in Cincinnati it was shown that the limits for commutation were very nicely brought out by changing the size and the relative proportion of the inter-poles. As has been said, the pole of half the length of the armature was found to be a desirable field. That may be true; at the same time if the shape of the pole is very much changed, I am satisfied it will be found that the number of ampere-turns on the inter-poles should be changed, depending somewhat on the width and the length of the inter-pole. The author says further:

> In cases where the teeth of the armature are wide, it is necessary to make the bevel of the edge of the pole quite wide.

That refers to the main pole. I am sorry that he did not dwell on the relation of the width of the commutating pole to the armature on which it is to be used. It is my opinion that there is room for considerable investigation along this line. The distance through which a coil passes during commutation, which depends on the width of the brush, the pitch of the slot, and the number of coils per slot—all these, I think, have a very great bearing on the proper proportion of the commutating pole. Referring now to the statement:

> With the inter-pole construction, as the fringe of the main field is not used for commutating purposes, the beveling or skewing of the edge of the pole may be much narrower, and therefore the effective pole area is larger.

This seems to mean that we can use a wider pole, or get the advantage of a wider pole-face, when we have introduced a commutating pole. Considering the fact that the commutating poles have to be provided for, and that they take up a certain amount of valuable space, we cannot use any greater pole in the enclosure than on the standard machine.

The matter of air-gaps on the machine is also of importance, and I think it is not well to reduce the air-gap too much. The flux in the main pole may be reversed, but causes increased iron losses which would affect the efficiency and temperature of the machine.

L. D. Nordstrum: In regard to the humming of the armature being eliminated or reduced by beveling the main pole. Is this humming the same as that spoken of by J. Fisher-Hinnen, as whistling, which is controlled by a certain relationship between the pole-arc and the pitch of the teeth? J. Fisher-Hinnen has given us an equation by the use of which we can adjust the relation of the pole-arc and the pitch of the teeth so as to eliminate, or at least to reduce to a great extent, this noise which he terms whistling. We have applied this equation in several cases to our machines and find that it works very satisfactorily. Is this humming related in any way to the whistling?

C. H. Bedell: The humming which I referred to is that produced by a tooth suddenly entering a strong magnetic field. The usual practice in standard design is to bevel the field so that the tooth will enter the field gradually. The skewing method used on the inter-pole motor is used largely on account of a simpler method for shop use, one end of the tooth entering the strong field before the other dampens the tendency to humming.

C. P. Steinmetz: Regarding the question of the use of the inter-pole on series motors: some years ago the inter-pole was used on single-phase alternating compensated series motors, and it was found useful in improving the commutation; but its use was not continued, because the advantages gained were not sufficient to offset the disadvantage of the lower power-factor due to the counter electromotive force of self-induction of the inter-pole coil. Its use involves the question of weighing the advantages and disadvantages. In another type of motor it may be advantageous. In direct-current series railway motors the question is still before engineers whether the advantages gained by the use of the inter-pole are sufficient to compensate for the disadvantages of a duplication of the number of field coils and field poles and the space occupied by the inter-poles. Experience and further investigation will decide that.

The inter-pole is not a new feature; it has been known for many years. I had occasion several times in former years to investigate the inter-pole, and under the conditions existing then decided against it. However, it is now used very satisfactorily and is a great success. It is one of those things like the single-phase alternating-current railway motor, or like the unipolar machine, which are not new inventions, but many years old—the unipolar machines have been known for a very long time—and the single-phase alternating-current compensated series motors were built and tested 15 years ago by R. Eickemeyer; not only machines in general lines similar to the present ones, but practically identical, even in the numerical proportioning of the parts, were built for low frequency, 30 cycles. Still they have only been used in the last few years, because 15 years ago, while the machine was practically there in all its parts and proportions, there was no call for it. No one wanted 30 cycle apparatus; no one cared to use alternating current on railways, because for all distances then considered direct current was satisfactory. It is only within very recent years that the great extension of long-distance electric railway lines has called for the use of the alternating-current motor, and so this motor was resurrected or re-invented, whichever you may call it, perhaps a little of both. The same is the case with the unipolar machine. To operate it satisfactorily requires large power capacity at high speed. There was no prime mover to give that large capacity at high speed until the steam-turbine came into use. The unipolar machine had to wait for the steam-turbine before it could become a commercial success.

If we consider the question of using the inter-pole in a well-designed direct-current machine, whether motor or generator, we find no advantage. It is a complication. But we can reverse the consideration and say: we do not take a good machine as it stands, but design the machine by the use of the inter-pole. The inter-pole, controlling armature reaction, allows us to re-design the machine with practically unlimited armature reaction, which we could not do otherwise, and still get good commutation.

Most of the features of this re-design have been discussed here to-day. The limitation of the output of a machine may be due to heating or to sparking. Where heating limits the output the inter-pole will not improve it. The development of the last years has been in increasing the output by better methods of ventilation, use of better material, which gives lower hysteresis loss, and a better method of insulating against eddy currents. This has largely increased the heating limit, so that machines formerly limited by the heating, are now limited by the commutation.

Again, the inter-pole permits an increased armature reaction, and a lower field excitation. We could not use lower field excitation before in many cases. To secure the best dielectric strength of the armature, it is advisable to have the armature coils wound and insulated and then dropped into the armature slots. That means straight slots in the armature, with a considerable opening of the slot. To reduce the heating of the pole faces by the eddy currents means then that either, with a small air-gap, laminated field pole faces are required, or the length of the air-gap must be not less than about half the slot opening of the armature. The laminated field pole is a complication which is not so objectionable now as it was years ago, and laminated field poles are now used to a great extent.

The maximum turns which you can put on the armature are limited by the pitch of the pole; that is, the armature diameter. It may be that the armature reaction which we could use, and the field excitation which we had to use to send the flux across the air-gap, was such that very little advantage could be gained by using the inter-pole. To get the benefit of the inter-pole meant much higher armature reaction; that is, very much higher peripheral speeds of the armature, larger armature diameter, a lesser number of poles; but larger section of the iron part of the machine, and other changes which, under conditions that existed years ago, made the machine more expensive and less desirable. With the change of industrial conditions and the use of higher peripheral speeds as required by the steam-turbine, conditions are entirely changed.

A very much larger pitch of the armature and so much higher armature reaction has to be used. The ampere-turns field excitation required to send the magnetic flux across the minimum permissible air-gap became far less than sufficient to control the armature reaction. Furthermore, to get a reasonably large number of poles and reduce the armature reaction within reasonable limits, required a low number of poles, say four poles in an 1800 rev. per min. machine, and that meant 60-cycle commutation. Hence the conditions of commutation became very severe, and in this case the inter-pole is a great success, while before these industrial changes had taken place, the inter-pole was of less advantage, and rather undesirable by reason of complication.

Now, as has been so ably discussed in the paper, by the adoption of the inter-pole in variable-speed motors, we get a very wide range of speed. This range of speed is secured by weakening the fields greatly, which means a high armature reaction. If you have two voltages in a system, say a three-wire circuit of 110 and 220 volts, and then in addition enter into the neutral of the armature by a compensator, connected to two opposite points of the armature by means of collector-rings—the center of the compensator representing the neutral or center of the armature—you can then utilize half of the counter electromotive force of the armature to consume the impressed electromotive force. Hence you get speeds corresponding to 110, 220, or 440 volts, or you get, at constant field excitation, a speed variation of 1 to 4.

Since ordinary field control will give a speed range of one to two, this combination then gives you a speed range of 1 to 8 without being obliged seriously to lower the field excitation. This is, however, a complication, and in all of these matters of engineering you must weigh complication against complication; the advantage of one feature against its disadvantages. The conclusions change with the change of the underlying requirements. Thus we find in the course of progress the inter-pole now being introduced on a large scale as a very great improvement, while during the past 15 years, since the time of its first proposal, it has not been used to any extent except here and there tentatively.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

SOME EXPERIENCES WITH LIGHTNING AND STATIC STRAINS ON A 33 000-VOLT TRANSMISSION SYSTEM.

BY FARLEY OSGOOD.

In this paper will be related the actions of the multigap series resistance type of arrester unit, and the multigap type of arrester unit without the series resistance, experienced during the years 1904 and 1905 on a 33 000-volt transmission system operated by the New Milford Power Company, of New Milford, Connecticut.

This power company's plant is situated on the Housatonic River, which coming down from the Berkshire Hills through a mountainous and hilly country, runs in a southerly direction nearly parallel with the state line between New York and Connecticut, and empties into Long Island Sound between Bridgeport and New Haven. The transmission line follows this river for about 4 miles, and then turns directly east and traverses for 56 miles a country which is nothing but hills and valleys, the altitude variations being about 1 200 ft. These facts are mentioned merely to show, that like very many other hydroelectric plants, this one is situated in an ideal position to receive the full force of all lightning storms, which, generally speaking, follow the courses of the valleys.

The station is water-driven. At the time covered by this paper the equipment consisted of six 1 000-kw. alternating-current generators, generating at 1 150 volts, and 503 amperes, three-phase, 60 cycles. Before leaving the station the current is stepped up to 33 500 volts by means of single-phase step-up transformers connected in delta. The step-down transformers at the sub-stations are connected part in delta and part in Y, without grounded neutral. The transmission line is of aluminum, the wires being strung on wooden cross-arms and wooden poles. Two lines of poles carry one circuit each from the station to the Waterbury sub-station, a distance of 30 miles. The two circuits loop through the Waterbury station, and run back on the same two lines of poles for a distance of about 3.5 miles, when they leave the main lines and take a line of single poles. One circuit is placed on each side of the pole, the wires extending to the city of New Britain, a distance of 26 miles beyond Waterbury. At about the middle of this Waterbury-New Britain loop, a loop 5 miles long consisting of one circuit extends into the Cheshire sub-station. This loop is controlled at a switch-house near the junction point with the Waterbury-New Britain circuits. The transmission wires are arranged in triangular form, 60 inches to a side, with the apex upward.

During the year 1904, the multigap series resistance type of arrester unit was in service. The equipment at the power station consisted of 16 units in series per phase, without any multiplex connections of any kind. These units consisted of 4 gaps and two 250-ohm resistance sticks each, making a total of 64 gaps and 32 resistances between each line and ground, and 128 gaps and 64 resistances between line and line.

The sub-station equipments were the same, with the exception of a multiplex connection between phases, consisting of 250-ohm resistance sticks of carbon, which were varied in number from three or four to six or eight between the phases.

During this season the major portion of the heavy lightning discharges was in the vicinity of the Waterbury sub-station, and on several occasions the lightning-arrester equipment was very badly broken up, even to the extent of destroying all the carbons, and all porcelain bases of the units of one phase, and nearly all of a second phase.

Generally speaking, No. 2 and No. 3 phase equipment underwent the severest actions. If the shock to the arresters was not sufficient to destroy the bases themselves, the carbon series resistance sticks would invariably break, thus destroying any protective effect the apparatus might have.

On four different occasions when there were severe lightning discharges on the Waterbury section of the system, the power-station end of the system received such increased potential that insulators on the high-tension bus-bars in the generating station were broken down. On two of these occasions the lightning-arrester equipment at the power station discharged with sufficient severity to break five or six of the carbon resistance sticks, but on the other two occasions the arrester discharge was very light indeed.

The breaking down of the insulators at the generating station, the breaking of the resistance sticks in the station arresters, and the breaking down of the arrester equipment at the Waterbury sub-station occurred on the same phase.

These bus-bar insulator breakdowns caused us to place reactance or choke-coils between the arrester equipment and the bus-bars. The coils, one on each phase, consist of 20 turns 6 in. diameter of No. 00 copper wire. These reactance coils were placed in service at the generating station during the latter part of the 1904 lightning season, and since that time no high-tension bus-bar insulator has broken down.

On two occasions the building up of current on the line broke down a large porcelain insulator supported by the slate base of the pigeon-coop through which the wires pass when leaving the building. Although only two insulators were actually broken down at this point, four of these insulators had to be replaced on account of the discharges to ground through them. To overcome the discharge difficulty at this point, the insulators were removed, and the slate bottoms of the pigeon-coops broken out, so that each wire came out of the building in a 38-in. air-space. Fig. 1 shows these pigeon-coops, and although the bottoms are not visible, the condition can be understood. It might be mentioned that the two actual breakdowns at the point just described were caused when the transmission line was grounded; once on the same phase as the grounded line, and once on another phase.

The most severe storms during the season of 1904 occurred on July 29, and September 8, when, in the first instance, almost continuous flashes were experienced for 17 minutes, and in the latter instance, incessant lightning discharges for 29 minutes. During the storm of July 29, the automatic circuit-breakers opened 7 different times, and during the storm of September 8 they opened 8 times. During neither of these storms, however, was any damage done to apparatus.

The circuit-breakers which opened were of the instantaneous type, which no doubt accounts in a large measure for their rapid successive operation. There were three lightning storms on the section of the system beyond Waterbury which did not affect the main part of the system (as it is known), which is the section between the generating station and Waterbury sub-station.

These three storms occasioned three openings of the breakers that were placed on the outgoing lines toward New Britain at the Waterbury sub-station; and these storms caused no damage to apparatus which could in any way be attributable to lack of action on the part of the protective devices.

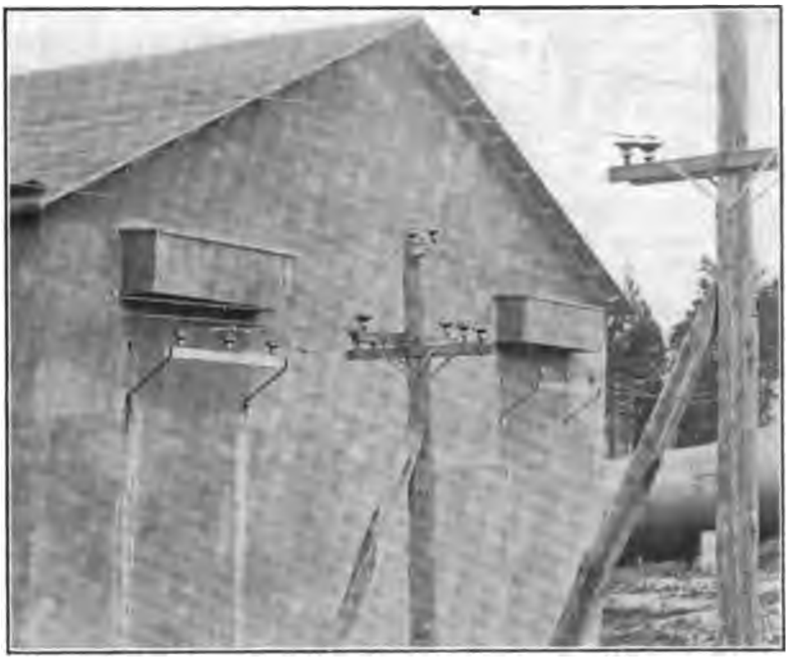


FIG. 1.
Pigeon-coops, Where Wires Leave Power Station, New Milford Power Co.

The record for the 1904 season shows that there were 19 lightning storms which occasioned 56 interruptions to service.

During the interim between the 1904 and 1905 seasons, the bellows-type time-limit relays were substituted for the instantaneous relays on the two lines going out from the power station, and on the two lines leaving the Waterbury sub-station for the New Britain end of the system.

These relays were set at 6.5 seconds at the power station, and at 4 seconds on the New Britain loop from Waterbury. It can readily be seen that disturbances on the far end of the line would cause interruptions only to the smaller sub-stations, Cheshire, and New Britain, and not affect the Waterbury service, which takes approximately $\frac{5}{8}$ of the station output.

The series resistance type of lightning-arrester was abandoned all over the system, and was replaced with the multigap type without series resistance. These units consist of 24 air-gaps each, and were arranged with 14 units per phase, with multiplex connection, without resistance, connecting the three phases, and a bank of 14 units between this multiplex connection and the ground, making a total of 672 gaps between line and line, and the same number between line and ground.

Reactance coils similar to the ones described above as being placed at the power station were placed at all sub-stations. Figs. 2 and 3 show the series resistance type of unit installation, and the " V " type multigap installation, both with choke-coils, as they were placed at the generating station.

As the multigap type of unit without series resistance had never been in service on any system, there was some doubt as to whether the lightning would discharge across 672 gaps, but our fears were not well founded, as will be related in a moment.

The season of 1905 was noteworthy as being particularly free from lightning storms, although in Connecticut there were two very severe ones; one on May 25, and another on July 10.

There are approximately 1 300 poles in each of the lines between the power station and the Waterbury sub-station. On May 25, the lines were being operated in parallel as far as Waterbury, both lines being strapped together at each end by a switch.

The lightning storm on this date struck the line itself. At pole 746, No. 2 wire was down, and insulator so completely shattered that it was difficult to find a piece large enough to bring home for a sample. At pole 549, No. 3 wire was down, and the insulator somewhat shattered and considerably melted; what was left of it having the appearance of a molten mass. At pole 521, No. 1 wire was down, but No. 1 insulator was not broken at all. No. 3 insulator was broken on the petticoat, the current having jumped through to the cross-arm and by way of the iron cross-arm brace to the pole and ground. At pole 746 the cross-arm did not have to be renewed. At pole 549 the arm had to be renewed and the pole re-gained. At pole 521 the cross-arm did not have to be renewed.

At the time the storm struck the line, the two lines were in parallel. The trouble on this line was discovered, and the load shifted over to the good line. The current was kept on the line which was in trouble to develop it. This whole occurrence happened within a period of 50 minutes. The arresters discharged very slightly at each end of the line. No inside apparatus was damaged at any point.

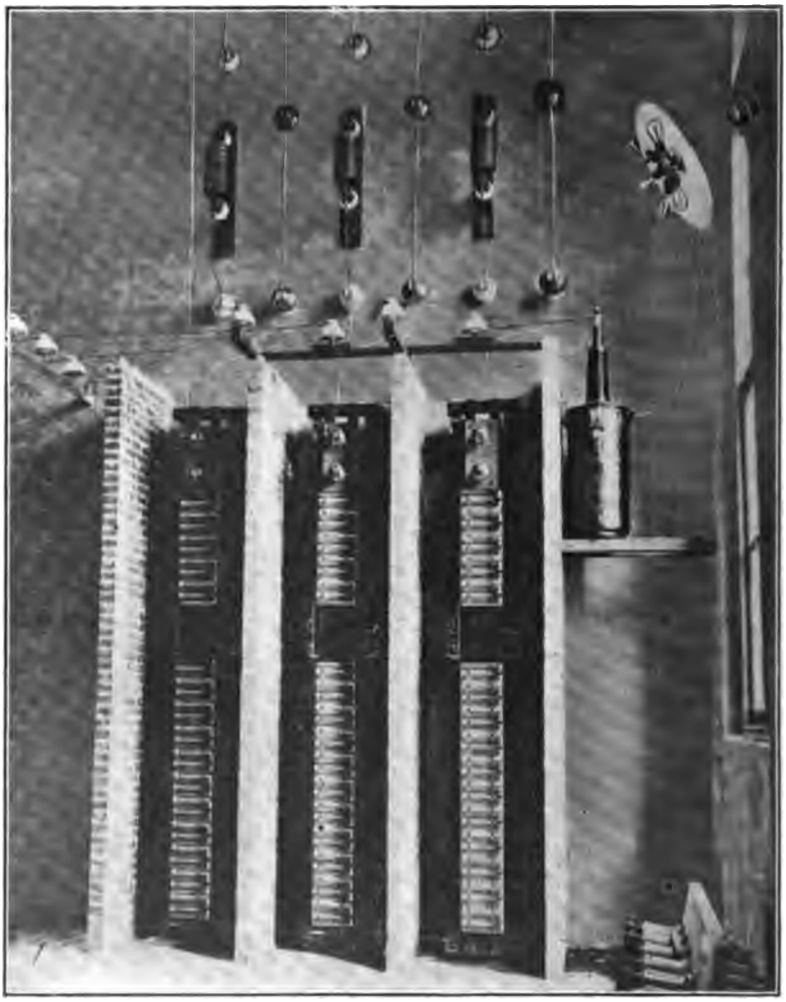


FIG. 2.
Air-gap Series Resistance Type of Lightning Arrester, with Choke-Coils, as Installed 1904 at Power House of New Milford Power Company.

On July 10 was experienced the most severe storm that ever has been known in this section. Soon after the storm struck the system, the lines which were being operated in parallel were separated, one line carrying the load, the other being held dead in reserve. Almost immediately after this change was made the arresters at the power station on the working line dis-

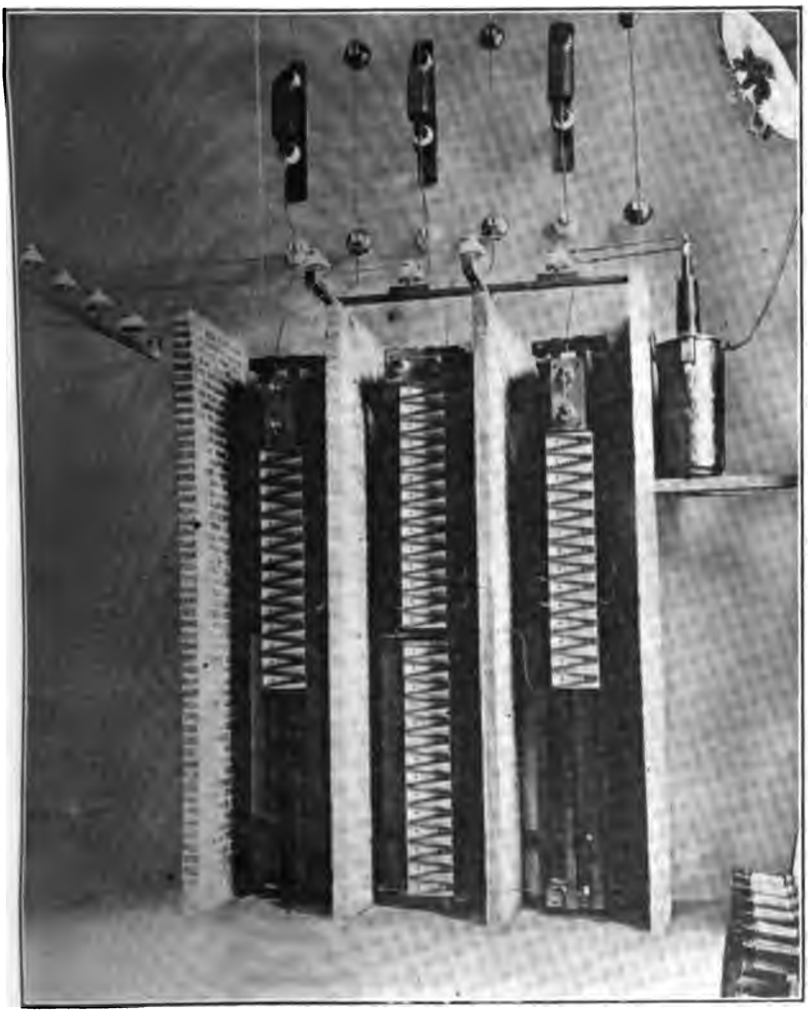


FIG. 3.
Type " V " or Straight Air-gap Arrester Units, Without Series Resistance, as Installed 1905 at Power House of New Milford Power Company.

charged across the multiplex connection and held an arc which was timed for a little over two minutes when the breaker was opened by hand to break the arc, the load being put on the reserve line. Examination of the arresters showed that all the cylinders were welded together, including the ground-bank, although the cylinders of the ground-bank were not so severely melted as the banks above the multiplex connection. None of the porcelain bases was damaged; although the compound from the screw holes was almost entirely melted out, and ran down across the face of the porcelain bases. Almost immediately after the load was put on the reserve line this set of arresters acted in the same manner as just described. The operator timed the arc for a little over a minute, and then pulled the breaker to save the arresters, as it was his last set.

All the units on all three phases above the multiplex connection had every cylinder welded together. Six porcelain bases were cracked, and the compound in the screw holes was almost entirely melted out. Although the bank of units between the multiplex and ground was observed to discharge, the cylinders were not welded together at all. This set of arresters was cleaned up and put back into service, but went out again almost immediately. The welding of the cylinders was about the same as on the first occasion. From this it is clearly seen that lightning *will* discharge across 672 gaps.

The arresters at all three of the sub-stations discharged slightly, but no harm came to them. Figs. 4 and 5 show the arrester tell-tale papers after this July 10 storm, and after a storm of July 22. It will be noticed that heavy discharges occurred only on one phase and the ground-bank. The papers are arranged showing the three phases on top, numbering from 1 to 3, from left to right, and the ground-bank below the multiplex connection, underneath. The power-station tell-tale papers were burned up during the storm of July 10.

Six poles were splintered at about equal intervals over the 56 miles of line. It was noted that but one of these poles was sufficiently damaged to warrant immediate replacing; the other five were splintered only in the lower half, no damage being done at all above 20 ft. from the ground. No damage was done to any apparatus during this storm.

The storm seemed to center in the immediate vicinity of the generating station. Continuous flashes of lightning occurred for 1 hr. 40 min. The action of the arrester cylinders shows

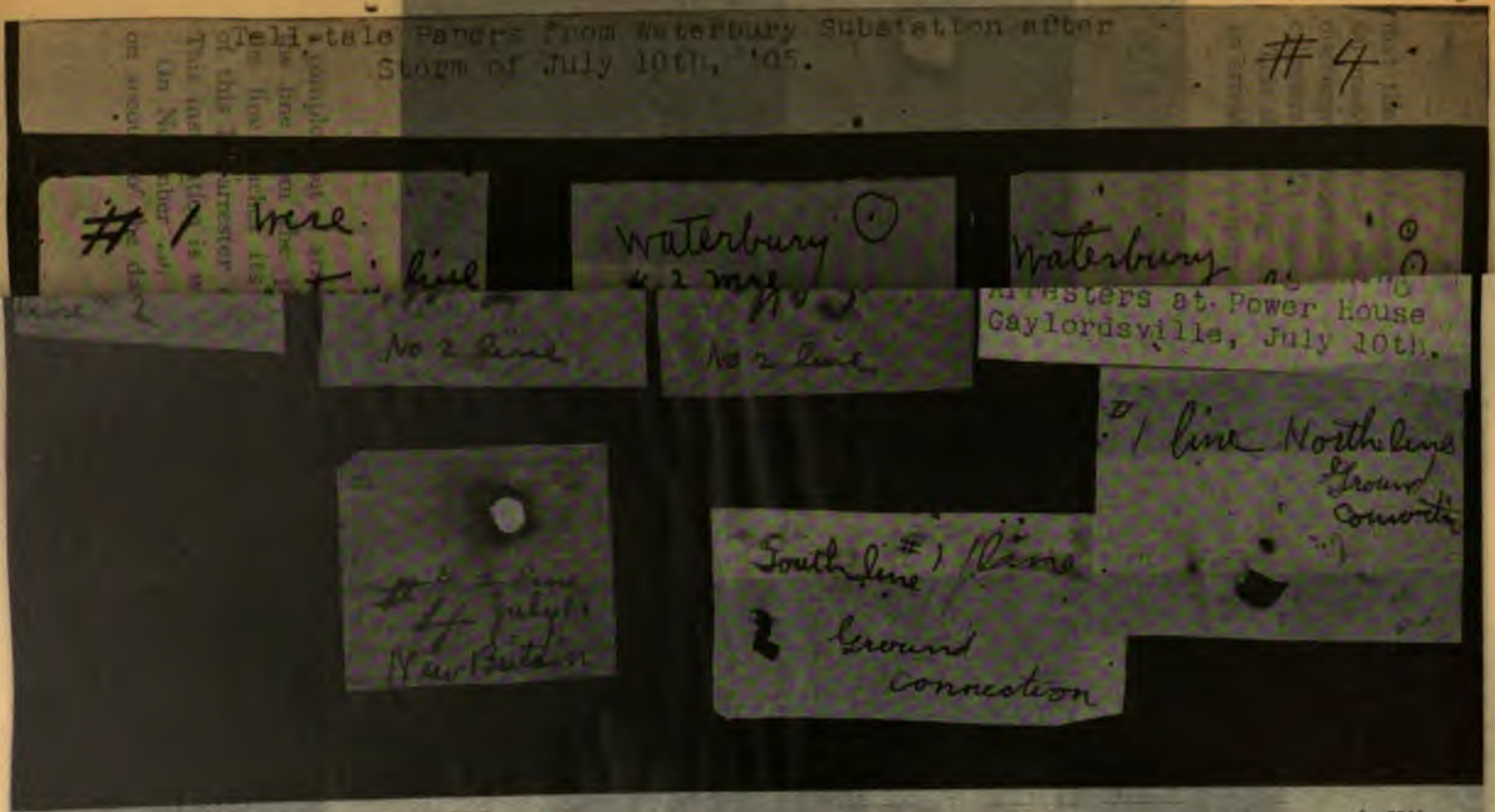
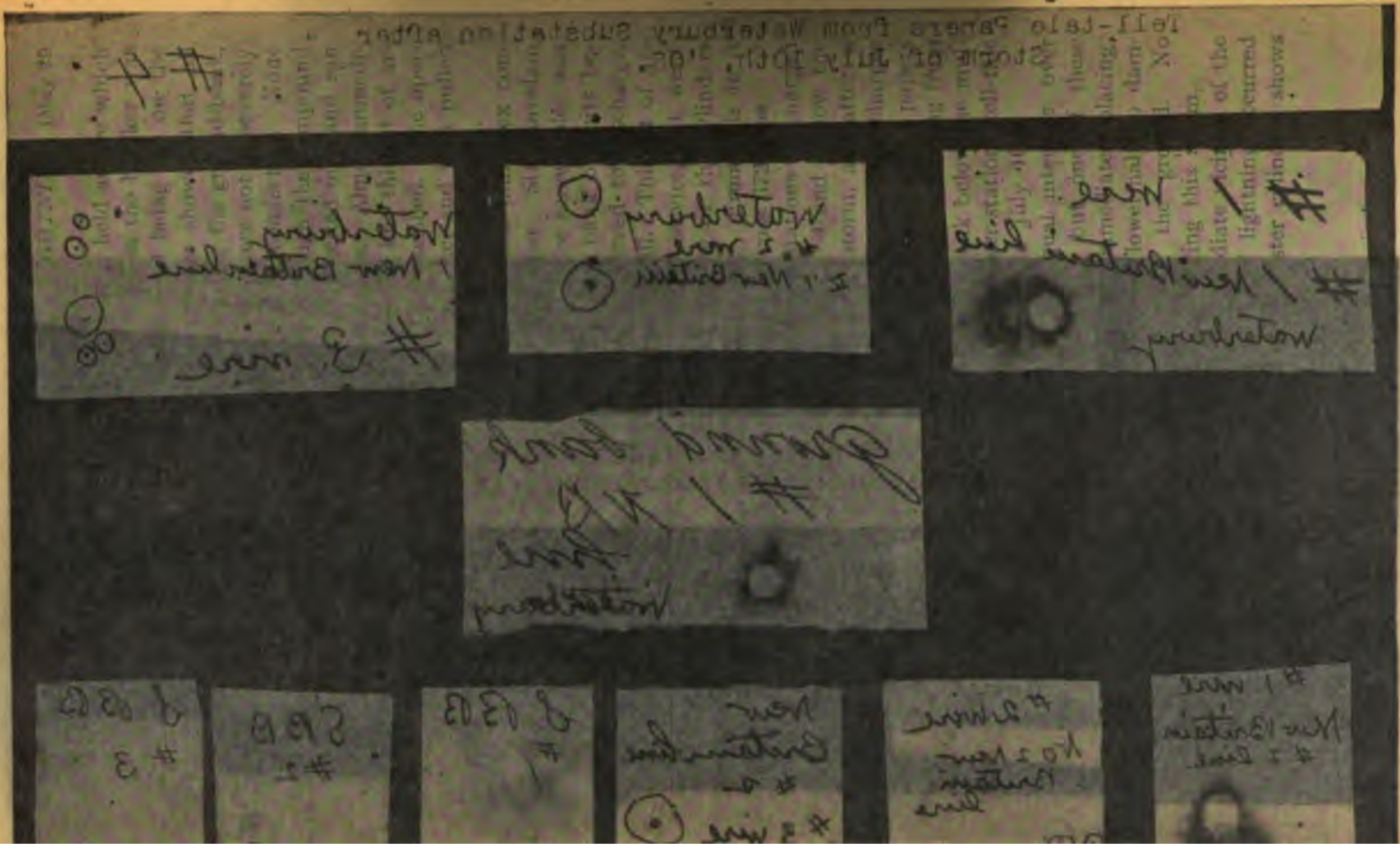

Tell-tale Papers from Waterbury Substation after
Storm of July 10th, '05.
#4
#1 wire.
line
Waterbury
#2 ...
No 2 line
No 2 line
Waterbury
Arresters at Power House
Gaylordsville, July 10th.
#1 line North line
Ground
Connection
#4 July
New Britain
South line #1 line
Ground
connection

FIG. 4.

[p. 356]



Tell-tale Papers from Waterbury Substation after Storm of July 10th, '08.

that the discharges of current must have been very great. On many other occasions the power-house arresters took all discharges successfully, and on no occasion did the arrester cylinders weld together at the sub-stations.

This shattering of the poles led us to consider the placing of an arrester equipment on the line. As soon as it could be done, a complete set of arresters was installed about 10 miles out on the line from the power station, on the top of a hill where the line reaches its highest altitude. Since the installation of this line-arrester equipment no poles have been shattered. This installation is within 10 poles of the sectionman's house.

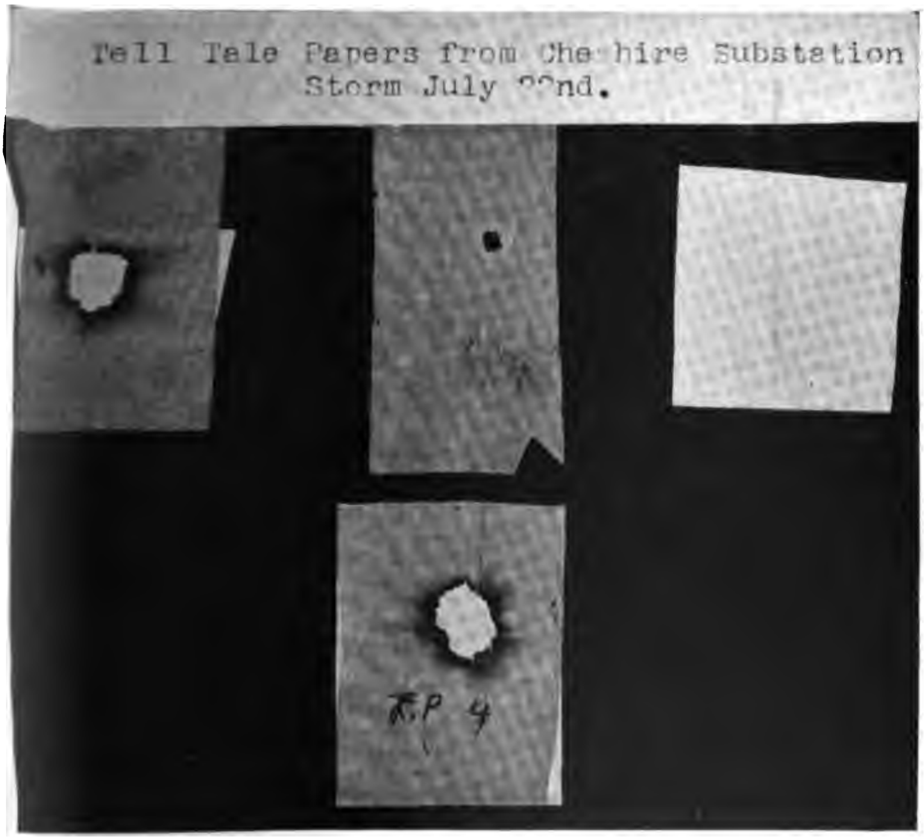


Fig. 5.

On November [illegible], 1905, a short circuit, which is interesting on account of the damage done to apparatus, occurred on the

New Britain end of the system. The two New Britain lines were in parallel, and some miscreant threw a steel umbrella-rod into the wires, short circuiting No. 3 phase of the No. 1 line and the No. 2 phase of the No. 2 line, these being the pole wires. The result was the burning out of two 550-kw. step-down transformers at the Waterbury sub-station, the piercing of the coils of a 330-kw. transformer at New Britain sub-station, and the damaging of a small potential transformer at the Cheshire sub-station.

This short circuit caused considerable trouble, as just described, whereas the short circuiting of the lightning arresters at the power station on July 10 and the short circuit on May 30 when all three phases of the line were on the ground caused no damage whatever to any apparatus.

During the season of 1905, there were four lightning storms which caused seven interruptions. As already stated, during the 1904 season there were 19 storms which caused 56 interruptions. The relative percentage of interruptions to storms is so largely in favor of the 1905 season, that we are led to believe we have made an advance in the betterment of our protective arrangements.

For the season of 1906 these arresters are being operated with resistance in shunt with a portion of the gaps, in the expectation that this will limit the dynamic current.

A telephone line is operated over the entire 56 miles of this transmission system. The line is strung on the transmission-line poles. This telephone circuit is of No. 6, B. & S. galvanized steel, is carried on brackets on each side of the pole, tied to a fairly heavy telephone trunk-line insulator, and is transposed between the poles every third section. The only protective devices on this line are ordinary telephone protective devices placed at the sub-stations, there being no protection for a man talking on the line should one of the high-tension wires happen to break, and fall across the telephone circuit.

It may be interesting to some of the members to know that in the latter part of May we made tests on a telephone protective device arranged as follows: on the instrument end of the device was a 1-1 transformer, or heavy repeating coil, built to stand a pressure of 2 500 volts. Ahead of this transformer was a ground-plate cut-out consisting of copper blocks instead of the usual carbon blocks, and separated by two micas of 0.0055 of an inch in thickness. Ahead of the ground plate was a tubular fuse of about 10 amperes, and ahead of this was a long fuse of 25 amperes' capacity.

Tests were made by varying the length of the long fuse from 6 ft. to 20 ft., and varying from 25 to 50 amperes. A separate telephone test-line of a few sections was put up to make this test, one side of the telephone circuit being strapped to one side of one of the transmission lines by means of a No. 10 copper wire, and the other side of the transmission line was then grounded. The ground-plate device of the protective apparatus also being grounded. 33 000 volts was then thrown on to the transmission line.

FIG. 6.
Telephone Protective Device Test; 6 ft. 25-Ampere Fuse.

The long fuse operated, as well as the tubular fuse, and the ground-plates operated. Many tests were made, the machine current being held on for some 15 to 25 seconds. The telephone instruments on the test line had their receivers off, thus giving the effect of the instruments being in service, and on none of the tests was any part of an instrument damaged in any way.

This led us to the installation of one of these devices on the power-house end of our telephone line, but it was found that we could not prevent the induced current on the telephone line from arcing across the ground-plate equipment of the arrester, notwithstanding the fact that we increased the mica separators to five in number. The ground-plate apparatus would hold up at times for several hours, and at other times would arc across immediately, thus showing that the induction effect on the telephone line was not constant, and for this reason the device was given up awaiting a further stage of development.

FIG. 7.
Telephone Protective Device Test; 20 ft. 50-Ampere Fuse.

By means of an ordinary portable voltmeter, we found that the telephone line carried 775 volts between one side and the ground, just outside of the power station, and 995 volts just outside the Waterbury sub-station. One reason for the high voltage on this telephone line is that the transmission line is not transposed at all.

Figs. 6, 7, and 8 show three of these tests.

Fig. 8.
Telephone Protective Device Test; 50-Ampere Tubular Fuse, 1 ft. Long.

The one with the power station in the background shows the arcing of a 6 ft., 25-ampere fuse. The one showing the long arc between the poles is a 20 ft., 50-ampere fuse. The one showing the smaller arc near the pole is a 50-ampere tubular fuse about one foot in length.

To prevent a water ram in the penstock at the time of the releasing of a short circuit, the penstock terminates in a stand-pipe 105 ft, high and 5 ft. in diameter. At the time of these tests we were fortunate in getting a photograph of the discharge of the stand-pipe, and the same is shown herewith.

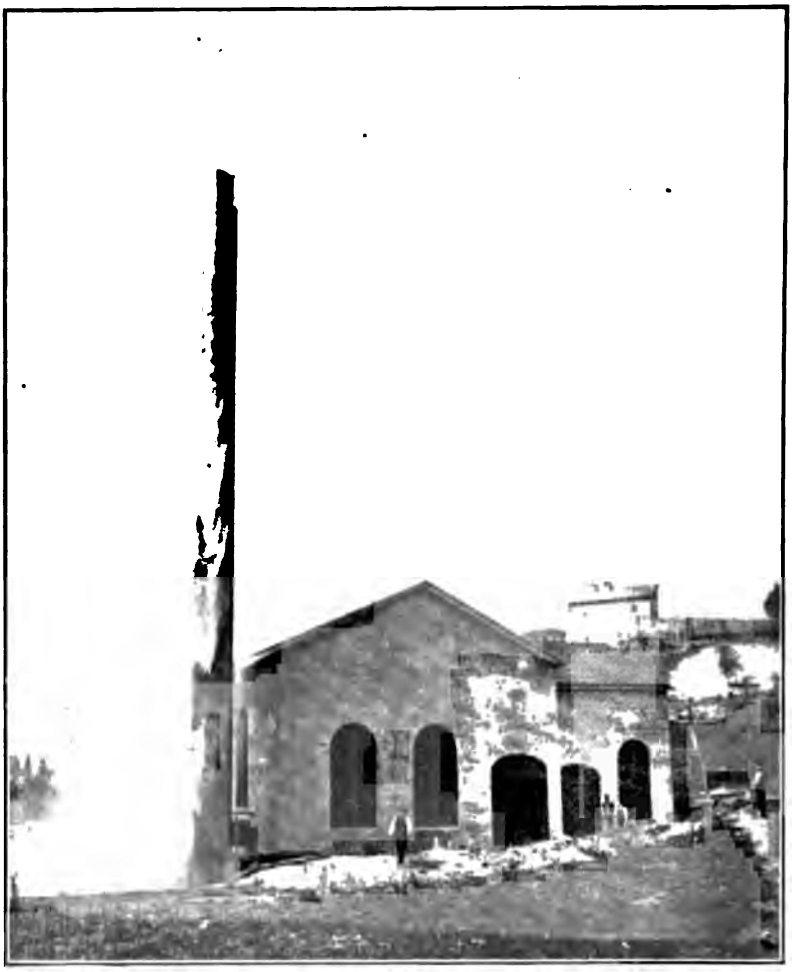


FIG. 9.

Discharging of Stand-Pipe, New Milford Power Co. Pipe 105 ft. High. 5 ft. Diameter.

A study of these two seasons of lightning experiences brings out the fact that our trouble has covered the whole system, and in no way confined to one point. We have done all we could to better our arrangement of protective devices as we have progressed, but the shifting of the location of trouble and the building up of high waves of current on the line make one consider the advisability of changing the connection of the transformers to a Y formation and grounding the neutral points.

These experiences also seem to indicate that it is the resistance in series with the gaps which causes the greater obstruction to the lightning discharges, rather than an increase in the number of the gaps themselves.

With the resistance in shunt with a portion of this greater number of gaps, and on account of the flexibility of adjustment of such an arrangement, it is expected that this year's experiences will develop the proper relation between series gaps, and shunted gaps; if such proves to be the case, this type of equipment will be comparatively simple to handle.

The relating of this detail is done with the view of putting before our members some experiences which may be different from those given in former papers, and in the hope that some additional studies may be worked out for the betterment of the protective devices to relieve us from the wonderful forces of our worst and common enemy, lightning.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

METHODS OF TESTING PROTECTIVE APPARATUS.

BY E. E. F. CREIGHTON.

This paper treats of the methods of testing arresters and dielectrics, and presents most of the conditions and precautions the writer has found necessary to observe to obtain useful results. A second paper will include more details of insulation tests, and will describe the application of tests to some new and some old types of arresters.

The general term lightning has been applied by Dr. C. P. Steinmetz to mean any abnormal surge of voltage on a transmission line. This is a convenient term, since lightning-arresters should be designed to protect against any dangerous rise in voltage, whether the clouds are the source or not. This designation will give a natural division of lightning into:

Cloud lightning from an external source.

Surge lightning from an internal source.

Both kinds of lightning usually appear together in summer; that is to say, surge lightning of a more or less serious nature usually follows cloud lightning, as an after effect connected with the extinguishment of the arc. Occasionally, at other times, surge lightning will appear unaccompanied by cloud lightning, due to bad methods or carelessness in switching, accidental grounding of a phase, or a short circuit.

There is no definite fixed practice in testing lightning-arresters corresponding to the well-known and satisfactory tests of every other piece of apparatus used in electrical transmissions.

The characteristic behavior of a generator, motor, transformer, meter, and even of switches, can in general be subjected to tests, in order that the apparatus shall fulfil the requirements of use. These requirements, such as overload capacity, regulation, accuracy, dielectric strength between the different parts at normal frequency, etc., are factors the conditions of which can be reproduced at will. On the other hand, lightning-arresters are designed to protect against the foe, " high-tension strain," that appears in many indefinite forms, and attacks different parts of the transmission system, according to circumstances.

Some of the forms of lightning stroke cannot be reproduced in the laboratory. Laboratory demonstrations have often been made of one particular kind and power of stroke in conjunction with a device which protects against that particular condition, but not against a number of other conditions met in practice. As a result, laboratory methods have fallen into disfavor and disuse. This condition is unfortunate, in that apparatus may be installed which is intrinsically unable to withstand even laboratory tests. It seems safe to adopt a rule used in the development of protective apparatus, to the effect that all protective apparatus must pass the laboratory and shop tests before it can be considered ready for the line test. It seems safe to say that sooner or later the arrester installed on the line will be placed under every reasonable condition that can be produced in the laboratory test, and besides, it will be subjected to other strains arising from new conditions, such for example as arise from increased static capacity, distributed capacity, and inductance, increased kilowatt capacity of generators, auxiliary oscillations, reinforcement of higher harmonics, disintegration from brush discharge, bugs, dirt, depreciation from use, and so on.

At the same time as stated above, all the elements are present on the line which could produce the effects of the laboratory tests. For example, although the total distributed capacity and the total inductance of a transmission line may be such as to give a low value of *proper frequency*, a higher frequency is possible by segmental oscillations on the line, as on a violin string; or a local circuit may be formed of small capacity and inductance, or high frequency may come from a neighboring spark, an arc, or cloud lightning. The range of frequency which must be considered in lightning protection lies between zero frequency (direct current) to about one billion cycles per second. Within this range there are certain values of frequency which may be counted on as absent; such, for example, are the frequencies between zero and the generator periodicity, and also those frequencies lying between the odd multiples of the generator frequency extending over a considerable range above the normal frequency.

The quantities of electricity involved vary from an immeasurably small quantity, through the range of comparatively small quantities tied up at different points of the transmission circuit in the form of electromagnetic and electrostatic energy, into the range of comparatively large quantities involved in line-current flow over an arrester subsequent to the passage of the electrostatic spark. Up to the time the line current starts the energy involved is inconsiderable, but the power is usually enormous. The successful arrester must be arranged to discharge this energy at its natural maximum rate of discharge. Any restriction of power increases the risk of high-potential strains.

On the other hand, when generator current follows, the almost incompatible condition of restricted power and energy must be introduced. The necessity for the rapid restriction of the passage of the generator power will become more evident when the laws governing the conditions of non-arcing qualities of metals are considered. This part of the subject, including methods of testing will be taken up later.

Summarizing: the factors of immediate interest are the rise of potential, the quantity of lightning electricity, the proper frequency of discharge, the frequency of recurrence of the lightning stroke, the power of the lightning stroke, the power and energy of the generator discharge.

The subject of lightning protection is particularly difficult on account of the uncertainty of the nature of lightning. Before apparatus can be properly designed we must know what conditions it must meet. Following is an attempt at a detailed list of the kinds of lightning or lightning effects to be found on a transmission line.

LIGHTNING EFFECTS.

1. Gradual static accumulations.
2. Sudden static induction due to cloud lightning.
3. Sudden static induction due to charging an adjacent line.
4. Sudden electromagnetic induction.
5. Direct cloud lightning stroke.
6. Oscillations due to grounding one phase of a delta system.
7. Surges due to grounding two lines through arresters.
8. Surges due to the interruption of the short-circuit arc.

9. Surges due to sparks between a line and an isolated conductor.

10. Surges due to discharges through a material of the nature of a Branley coherer or bad porcelain; also wireless telegraph waves.

11. Surges due to the short circuiting of one or more coils of a transformer or generator.

12. Surges due to closing a switch on an open line.

13. Surges due to closing a switch on a transformer at any point in the magnetic cycle but the right one.

14. Surges due to opening a switch on a loaded line.

15. Surges in three-phase systems due to third, ninth, and fifteenth harmonics.

It is not the object of this paper to treat in detail the foregoing enumerated lightning effects. It suffices for the present to classify the effects according to the frequency, quantity of electricity, and time of application, and attempt to reproduce, as far as possible, the same conditions in laboratory tests.

METHODS OF TEST.

First. Direct-current static potential test.

Second. Alternating potential from an alternator. Time of application variable, usually long.
  (a) At alternator frequency.
  (b) Metallic ground: harmonics to about the 21st.
  (c) Arcing ground: high frequency (300000 cycles).

Third. Disruptive-stroke test.
  Simple disruptive-stroke circuit, direct-current or alternating-current discharge.
  Dielectric spark lag.
  Proper frequency, four million or less.
  Time of application of potential, short.
  Frequency of applications of potential variable.

Fourth. Inductorium test.
  100 000 cycles.
  Continuous application, or variable.

Fifth. Half-wave test.
  Electromagnetic recoil—variable unidirectional potential.
  Time of application, short.

Sixth. Arc-extinguishing quality test.
  Rectifying limit set by splashing of molten metal.

First Test: gradual accumulation of static. These static charges on the line are due to the wind, rain, etc., and there seems to be no difficulty in conducting them to earth. There is more than one way of accomplishing this; one of the simplest is to connect three transformers **Y,** and ground the neutral.

The effect of steady static strain on insulation can be reproduced in the laboratory by direct connection to a static machine Fig. 1. As a matter of abbreviation, this machine-gap is invariably designated in these notes as the (*G*) gap.

Second Test: the second method of test (Fig. 2) is the one usually applied to dielectrics; that is, direct connection to the secondary of a transformer at commercial frequencies. This test can be made to include the 15th enumeration in the foregoing list of lightning effects; that is, the 3d, 9th, and 15th harmonics.

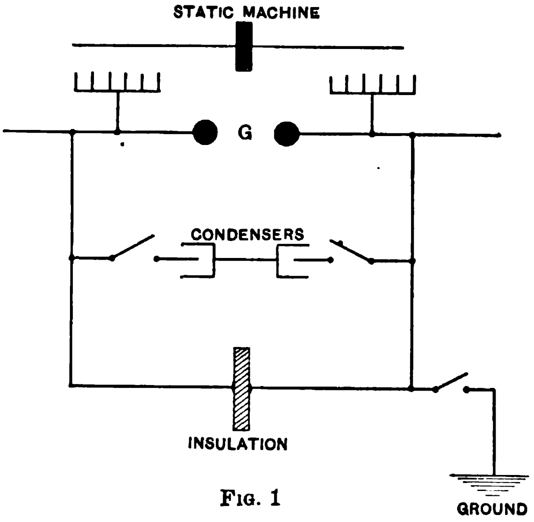


Fig. 1

The voltage should be read in this case by a voltmeter through the transformation ratio and also by needle gap. The two values may be widely different in either direction. Attention should be directed to the cause of the difference.

If the voltmeter through transformation gives a voltage above that indicated by the needle gap when the insulation ruptures, it can almost invariably be traced to a leakage of current on the secondary. This current will affect the value of the ratio of transformation by an amount depending upon the regulation and the kilowatt capacity of the transformer. The fault is eliminated by using a larger or better transformer. If the fault exists, one must depend on the needle gap to give the voltage. If there are no high-frequency oscillations, the needle-gap voltage can be depended upon within a few per cent. This is sufficiently accurate for insulation tests, because there is a wider variation in the dielectric strength of the same material at different places, due to the lack of homogeneity.

On the other hand, if the needle gap indicates a voltage greater than that shown by the voltmeter, it is evident that high-frequency oscillations are present. If the whole circuit is visible, the observer will see the cause of the disturbance.

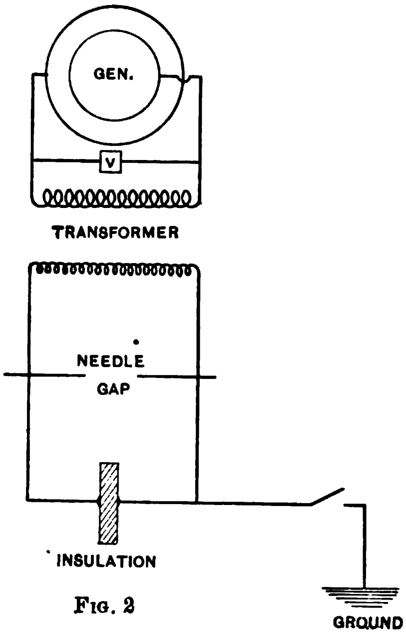


Fig. 2

Overflow spark streamers or corona effect produce local surges which bridge the needle gap with a blue brush-discharge. If the absolute equivalent needle gap is to be found, it is necessary to increase the needle-gap length considerably. The amount of corona effect depends on several factors; the most noteworthy are relative dielectric strength of the material, the impressed voltage, and the size and dissymmetry of the electrodes. The effect of the dissymmetry of the electrodes was strikingly brought out by a series of tests undertaken in conjunction with

Messrs. W. S. Moody and J. J. Frank. In these tests one electrode was a flat plate and the other a sphere. Static streamers would cover more than two square feet of surface without puncturing the insulation. The voltage indicated by the needle gap was at times 25% greater than the voltage by voltmeter and transformation. The question arises, which voltage to take as the dielectric strength under working conditions? The answer is—neither. The discussion of this involves the study of insulations with potentials applied for relatively long periods, and consequent gradual disintegration. Except as it comes under the 6th enumeration; that is, one grounded phase on a delta system, it is outside the scope of this paper.

Due regard to details will save much time in testing.

Dr. C. P. Steinmetz in a paper before the INSTITUTE in 1893 showed that it was necessary to place fresh sharp needles in the gap after each arc in order to obtain consistent results. The natural variations in the structure of most insulators is considerable.

To get consistent results the average of a number of tests must be taken, and the renewal of needles for each stroke would make the test endlessly laborious. To avoid this labor, the same needles are used continuously or renewed only occasionally. By setting an automatic trip-switch in the primary at a current value slightly above the excitation of the transformer, and attaching thereto the field switch of the generator, it is possible to cut off the energy from the secondary before very great damage is done to the needle points. After a few strokes the needles are dulled to a condition that they will retain for a considerable time. A spark-gap curve of the needles in the slightly dulled condition is taken and checked from time to time.

In the foregoing, the high-frequency oscillations were due to the testing electrodes. The same effect on the needle gap can be produced by oscillations in another part of the circuit. The most common source of oscillation in practice is due to grounding one of the wires. Grounding one line holds it continuously at zero potential; and since the difference of potential generated in the transformer remains the same, the other terminal rises to an absolute voltage twice as great as in the condition of no-ground. Grounding unbalances the internal static capacity of the coils relative to the core and earth, and a condenser current flows to the earth. The value of this condenser current depends upon the size and construction of the transformer, the voltage, the upper harmonics in the generator wave of electromotive force relative to the condition of resonance, the auxiliary capacity external to the transformer static capacity, and the continuity of the ground-circuit.

Internally in the transformer there are two directions in which the displacement current flows from the primary coil to ground: 1st, displacement current straight from primary to the iron. If the transformer case is insulated, a spark can be obtained between the case and ground. 2d, displacement current from secondary to primary, thence to the generator, and then another displacement current through the generator insulation to the ground. This is a condition of two condensers in cascade. The law of division of electromotive force between the two condensers is inversely as the static capacity of each. Fortunately the natural conditions of construction of a generator gives it a capacity much greater than that of the transformer, and its proportion of the secondary voltage of the transformer is correspondingly small. This phenomenon is far from negligible in the shop test where small generators are sometimes connected to large transformers. Some time ago while making grounding tests on lightning arresters we were charged with the destruction of the insulation of a 500-kw. generator of the rotating-armature type; sparks jumping from the end of the shaft through the air to the babbit-metal bearing were observed by the attendant. Since we had taken reasonable precautions, we finished the tests; the regular high-potential test was then applied to the generator, and the insulation was normal. The remarkable thing about this occurrence is the unbroken dielectric strength of the lubricating film of oil in the bearing. It suggests a method of ascertaining the condition of lubrication in a bearing. I recall having seen some insulation tests by Dr. A. E. Kennelly on this oil-film resistance.

Grounding one phase of the generator does not remove entirely the danger which may arise from special combinations of generators and transformers, because it is possible to ground but one phase, and a surge of high frequency may start from another phase and be compelled to discharge through the impedance of the generator coil. It is better to trust to good lightning arresters, properly adjusted, placed on each phase of the generator. If the conditions are excessively bad there still remains a slight risk due to local surges. Even these local surges can be avoided by a method to be described later.

Returning to the consideration of the harmonics in the generator wave, resonance, and continuity of the ground circuit; we find if the ground circuit is continuous (*i.e.*, no arc) that the upper harmonics in the ground current wave are apparently reinforced according to the frequency that corresponds to the resonant condition of inductance and capacity in the equations

$$N = \frac{1}{2\pi\sqrt{LC}} \text{ or } \frac{1}{C\omega} = L\omega$$

It may be stated in general that there is no very great increase of needle-gap length due to a metallic ground. This is due mostly to the conditions of generator design. The commercial alternators have comparatively few upper harmonics in their voltage waves, and these harmonics are of relatively small value; consequently, although the capacity and inductance may correspond to exact resonance, the resistances and losses involved usually prevent any very great increase in potential due to the reinforcement of a harmonic by the condenser. Furthermore, since the resonant point is very sharply defined, the chances of accidentally obtaining the right capacity for any particular harmonic are very small. Fig. *P* shows an oscillogram of the ground current taken by Mr. L. Robinson for the writer. There are twelve teeth on this generator per phase, and it will be noted that the $n - 1 =$ 11th harmonic is reinforced. Fig. *Q*, taken on another circuit with the assistance of Mr. C. O. Von Danenberg, shows by its wavy nature the reinforcement of the different harmonics with the increase of capacity. These tests were made on the Schenectady lighting circuit. The electromotive force is measured by meters in effective values. The needle gap, however, is sensitive to the maximum value of electromotive force, and would no doubt show a much more marked effect than a voltmeter.

If in Fig. 2 the ground is made by the formation of a spark, or arc across the ground-switch, this arc will reinforce the harmonics. The needle gap must be lengthened as the arc is drawn out. The maximum needle gap is obtained at the maximum ground arc length. Figs. *S* and *T* show the effect by means of oscillograms. Oscillograms in Figs. *Q*, *S*, and *T* are all from the same circuit. They show respectively; metallic ground, short arcing-ground, and long arcing-ground. Aside from these harmonics there are higher ones which the oscillograph is unable to measure. On another generator and transformer, with the assistance of Messrs. L. H. and J. B. Peebles, these higher frequencies were measured. They were of the order of 300000 cycles, and increased in frequency with the increase of the gap length.

Since the needle gap as a potential indicator measures maximum values of voltage, the increase in the values of needle-gap voltage, over the potential by voltmeter, when ground oscillations are present, may be satisfactorily explained by the presence of the peaks of the upper harmonics superposed on the fundamental wave. Since the harmonics oscillate across the fundamental wave, the difference in the effective value of electromotive force as shown by the voltmeter will be small compared to the percentage rise of the peaks of the harmonics over the maximum value of the main wave.

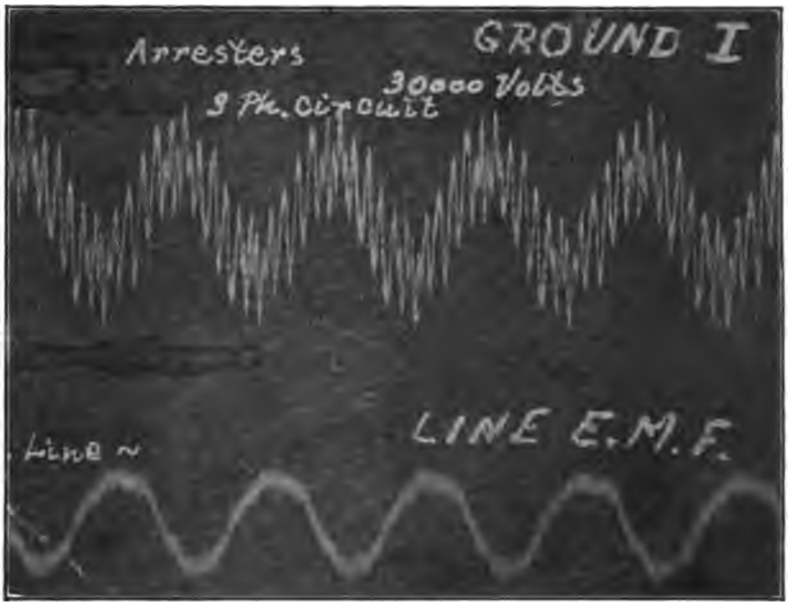


FIG. P.

When a multigap connection is made between line and ground, the frequency rises above a value measurable with the instrument we have. The proper frequency from the calculated values of inductance and capacity of the cylinders is of the order of a billion per second. At this frequency, spark and brush discharge effects are produced, which lead us to suspect that frequency may have something to do with the spark voltage. A train of queries is brought up by this phenomenon regarding the exact nature of conduction of electricity when the displacement current reaches the first stage of luminosity.

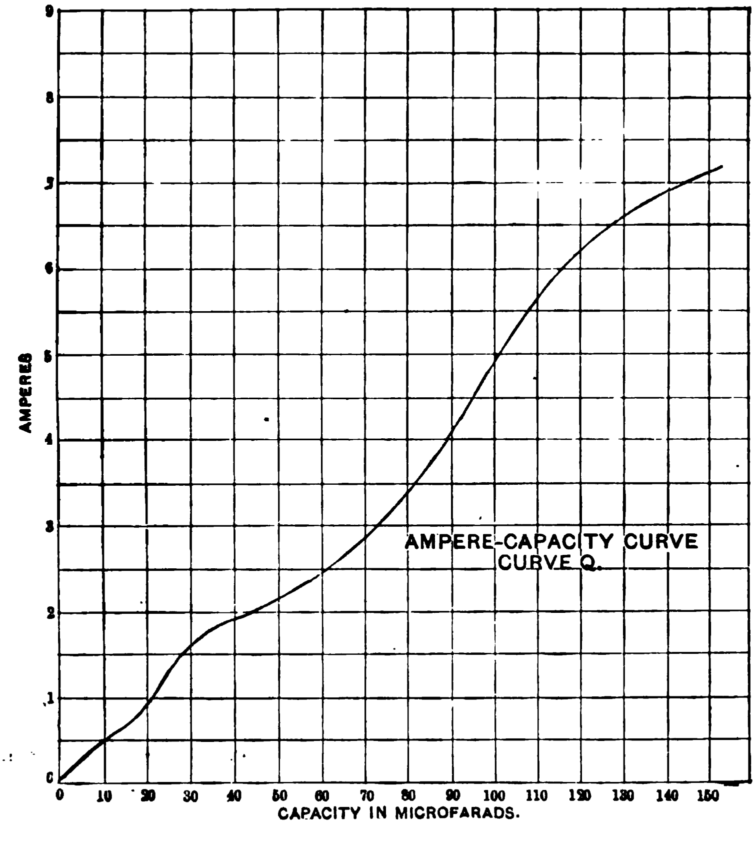


Fig. Q.

This part of the subject has a practical bearing on the question; do the proper oscillations of the multigap arrester weaken the insulation of the electrical apparatus? We have been unable to find weakening of the solid dielectrics due to the high frequency effects. The frequencies are so high that the effects are local in character. Something more about this may be said when the multigap arrester is considered.

The effect on the needle gap of grounding one line is shown on curve sheet 2b. The upper curve shows the relation between kilovolts and spark-gap length when all extraneous oscillations are eliminated, so far as possible. The second curve shows the same relation when one line is connected metallically to the ground. The lower curve shows the same relation when one line is grounded through an arc. It may be stated approximately that if an alternator is the source, any simple needle gap represents a range of voltage of at least 100% over the minimum voltage. The particular value of voltage in this range will depend upon the value and location of high frequency oscillations in the circuit. These oscillations in the above case depend greatly on the length of ground-arc.

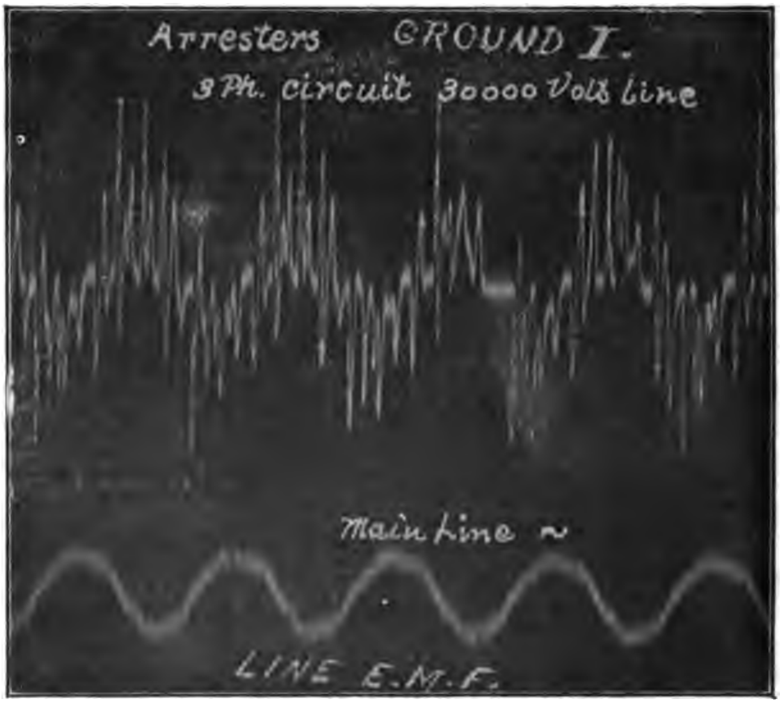


FIG. S.

Looking at this phenomenon from a converse standpoint, an experiment can be made in which the gradual increased tendency of needle-gap spark becomes visible to the observer. In this experiment the needle-gap length is set at a given value, and a voltage considerably less than that given by the A. I. E. E. spark curves is impressed. A ground-arc is then gradually drawn out from one line, and a brush-discharge will start from each needle and increase in value as the arc is lengthened. Under a different condition which cannot be described in this paper, it is possible to cause the brush-discharges to approach each other nearer and nearer, and finally to maintain a solid blue brush-discharge from needle point to needle point without the passage of a spark. The conditions are unstable, however; the more intense part of the brush is liable to turn into a spark streamer. This is indicated at times by a tiny yellow thread

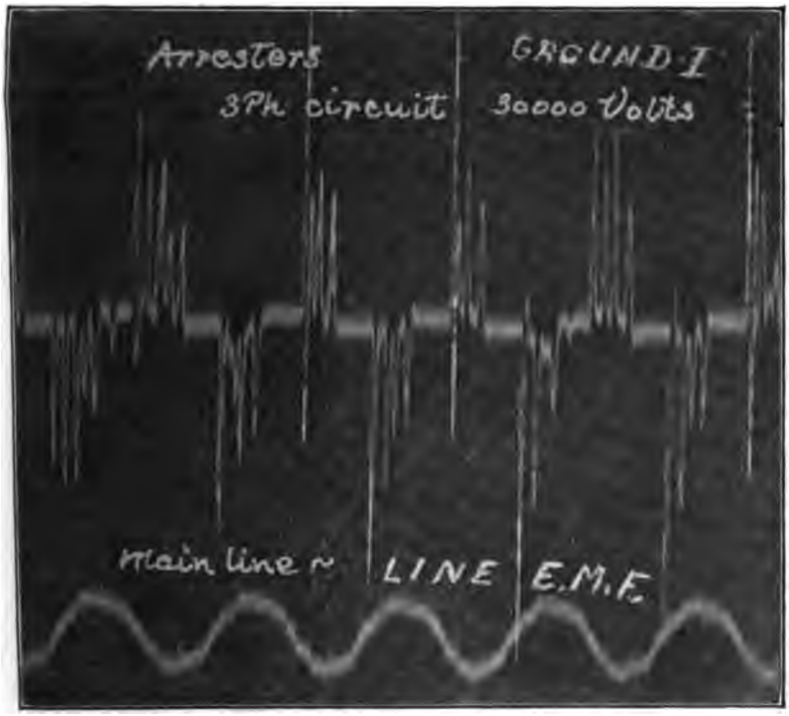
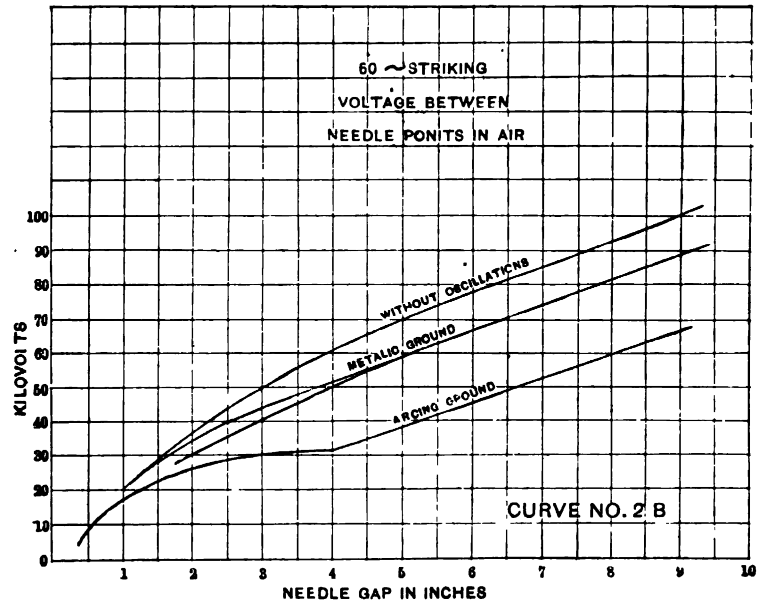


Fig. T.

which appears in the brush. At other times, especially if the voltage rises somewhat, these yellowish threads of light snap into a discharge familiarly known to test men as a " B. D. S. I." (breakdown at short intervals). This B. D. S. I. spark differs from the ordinary spark at a needle gap in not causing a short circuit of the transformer. In the light of other experiments on disruptive discharge, the explanation of the phenomenon would seem to be as follows: at the initial voltage where a brush-discharge is being formed into a spark, or rather where a spark is being formed in a brush-discharge, the change of ohmic resistance from a high value to a low value requires an appreciable time. During this interval the electromotive force has receded from its maximum value. The resistance drop and the voltage drop are literally racing toward zero. The resistance drop gets ahead and an insipid arc is formed which, however, is extinguished when the electromotive force wave passes through its zero value. The same effect can be caused in the multigap arrester by means of a synchronous switch, described below, which can be arranged to close the circuit on the decreasing values of electromotive force. The energy



loss in the arc is too small to aid materially in establishing the current in the reverse direction.

In the above case the blue brush-discharge damages the air insulation and the needle-gap spark length represents a dangerous condition. On the contrary, however, other dielectrics will conduct the same value of brush-discharge without materially affecting the dielectric strength. The time of application in this case has never been carried beyond an hour. Slow disintegration is possible under constant application over long periods of time, but the subject is only distantly related to lightning conditions. The needle gap is the only instrument that has been relied upon to give maximum values of potential. It may do so under conditions described above; if so, it is not voltage alone we want to know, but also how the voltage is produced and what the nature of the insulation is.

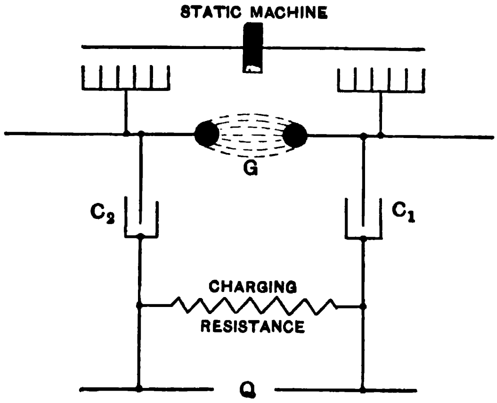


FIG. 3

Third Test. The third method of test of arresters and insulation is the disruptive-stroke test.

A simple disruptive-stroke circuit is represented in Fig. 3. The static-machine gap is marked *G*. To each electrode of the machine is attached one or more static condensers C_1 and C_2. The other plates of each of these condensers is joined through a high-resistance path designated as the *charging resistance*. Across the charging resistance is placed the measuring needle-gap *Q*.

When the machine starts, the combs collect the static electricity and charge the electrodes, one positively and the other negatively. There are two displacement currents through the dielectrics, or in other words there are two parallel circuits of condensers. There is a displacement current across the G-gap and its vicinity, representing a small quantity (q) and small energy $\frac{1}{2} q V$ stored up in the G-gap as a condenser. The other displacement current is through the insulation of the condenser C_1, through the charging resistance, and through the insulation of condenser C_2. The energy in this circuit is relatively much larger; it is represented as before by the equation $\frac{1}{2} Q V$ or $\frac{1}{2} C V^2$, where C is the capacity of the condensers C_1 and C_2 in cascade. So long as the potential V across the G-gap is increasing, there will be a current flowing across the charging resistance. Consequently there will be an $I R$ drop which will appear at the needle-gap Q. The $I R$ drop may become sufficiently great to cause the needle-gap Q to brush or even to spark. This is a condition of test which should be avoided in general, as it is equivalent to making the Q-gap smaller by giving it a considerable degree of conductivity. The simplest cure is to charge slowly. High resistance graphite or carborundum rods, if used as charging resistance, should be closely watched. They heat from the static energy and change their resistance, and furthermore in the megohm rods some action analogous to that of a " wireless coherer " may be present. When the condensers are fully charged, the potential across the needle gap is zero. When the potential V across the G-gap reaches the disrupture value, either of two effects, depending on whether a spark passes at Q or not, takes place.

Assume first that the needle gap Q does not spark. The machine gap G will be bridged by a weak disruptive spark of an oscillatory nature which discharges the small quantity (q) in G as a condenser. The condenser G is thus short circuited. The bound charges in the condensers C_1 and C_2 are released, and practically the full potential V appears across the charging resistance and the needle-gap Q. Since Q does not spark, the charging resistance commences to discharge the quantity of electricity in the condenser at the rate $V/R = I'$. Since in general the charging resistance is high, both the potential across the resistance and the quantity of electricity in the condenser decrease along a logarithmic curve as the time goes on. The condensers do not have time fully to discharge before the spark at the machine gap G is extinguished and opens up the circuit. The potential that existed across the charging resistance at this instant now reappears at the machine-gap G. Recharging continues from the static machine, and the cycle is repeated.

Assuming in the second place, that the needle-gap Q is set at a value that allows a spark to pass when the potential from the condensers C_1 and C_2 is applied. There is a vivid white flash at both the machine-gap G and the needle-gap Q, accompanied by a sharp loud report that makes it unmistakable with the first condition. The resistance in the main condenser circuit is reduced to a small value, thus allowing the discharge to become oscillatory. At the same time some current flows over the resistance, depending on the equation $I' = V/R$ and drops the potential slightly at the terminals of the resistance by a reduction of the quantity of electricity.

The current across the needle gap depends upon the frequency, potential, and condenser capacity.

$$I_2 = V\,C \times 2\,\pi\,N$$

It is comparably much larger than the current over the resistance. The frequency N of oscillation is equal to $\frac{1}{2\,\pi\,\sqrt{L\,C}}$ where C is the combined capacity of C_1 and C_2, and L is the inductance of the circuit through G-gap, C_1, Q-gap, and C_2. This current should have at least sufficient energy back of it to tear a considerable hole in a thick piece of pressboard. The oscillations gradually die out as the energy is dissipated in heat and radiant energy.

Some of the values of the several quantities usually used by the writer are: $V = 150$ kilovolts; $R = 0.4$ megohms; initial current over the resistance 0.4 amperes; initial current of oscillatory discharge something over 1 000 amperes, and frequencies from four million per second down.

Coming next to the subject of measurements, it is desired in this case to measure the " equivalent needle gap " of the resistance. The term equivalent needle gap is one that has been so loosely applied as to have no real significance. Oliver J. Lodge introduced the method of test, in what he termed the alternative path experiments*. The equivalent needle gap may naturally be taken to mean that the needle gap is set at such a value that the discharges choose the needle-

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*See Lodge's Lightning Conductors.

gap path as often as the other path. This is a quantity which has little practical value in lightning-arrester testing. The needle gap is supposed to represent the value of voltage that is applied to the insulation by a disruptive stroke. What we desire to know in the case of an arrester is the value of the needle gap placed in parallel with it such that the needle gap will never spark; that is to say, it is supposed to measure the voltage limit at the terminals of the arrester. Fig. 3a shows curves which emphasize the difference in equality and limiting values of needle gaps. The abscissas represent the lengths of the machine-gap *G*, which are proportional to the impressed potentials, and the ordinates represent the corresponding values of needle-gap lengths. The upper curve is the limiting or absolute equivalent needle gap, the next curve below is a favor-curve in which the spark discharge favors the resistance ten strokes to one over the gap, the lower curve is a reverse favor-curve in which the discharge favors the needle ten times to one over the resistance. Lodge's alternative-path curve should lie midway between the favor-curves. There seems to be a certain number of accidental conditions which help or prevent the spark at the needle gap. There is fortunately a very great consistency in the recurrence of these accidental conditions, so that values of equivalent needle gap can be checked within a few per cent. if the other conditions relative to the test are reproduced. Since it is the limiting needle gap that is of interest and is used most often, it seems preferable for brevity's sake to use the term equivalent needle gap to mean the limiting value; *i.e.*, the value of needle gap that will just not take a spark in 50 disruptive strokes. Any other condition may be designated as in the favor-curves described above.

It will be seen from the curves of Fig. 3a that the equivalent needle gap of a resistance depends upon the quantity of electricity to be discharged. The quantity of electricity in this case depends upon the impressed potential; an increased quantity might also be obtained by increasing the condenser capacity. By these means the equivalent needle gap of resistance lies anywhere between zero and the value that will cause the resistance to spark over, according to the quantity and voltage of the discharge.

The capacity and quantities of electricity available in the laboratory are usually quite small compared to the same quantities on a transmission line. Nevertheless the laboratory tests are of importance, in that the relative conditions can be roughly compared and some idea formed of what might occur if the same resistance were used in a lightning arrester on a transmission line. There is one rule, at least, that is safe to adopt

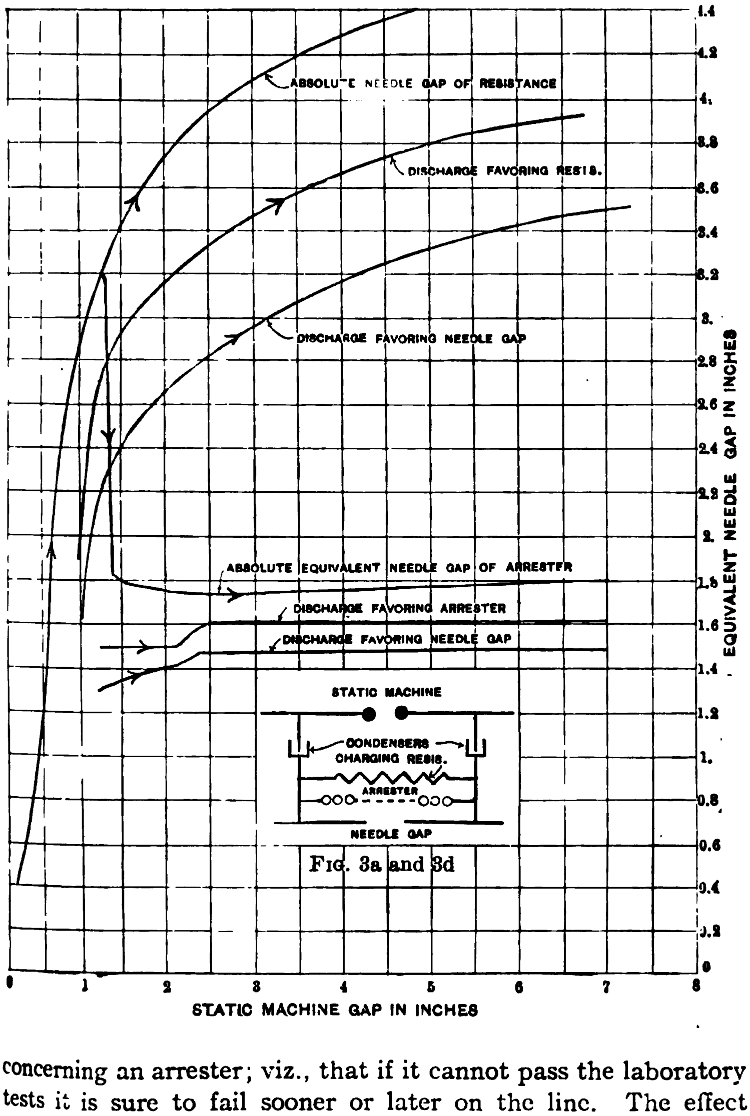
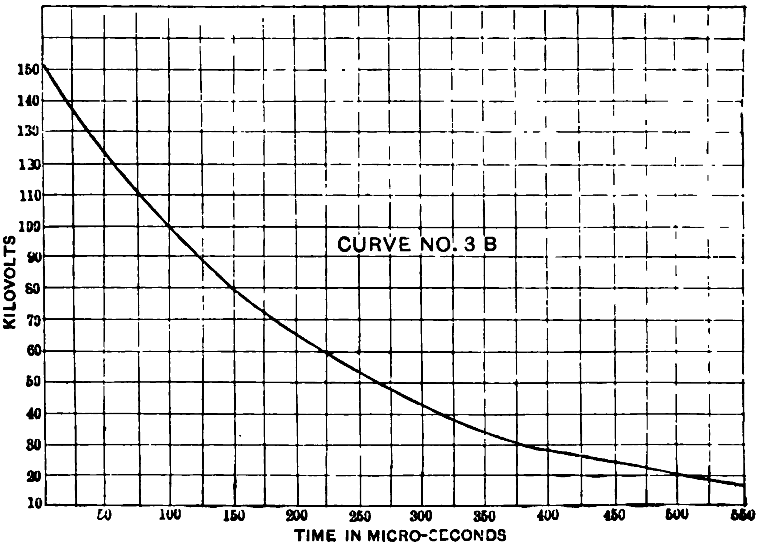


FIG. 3a and 3d

concerning an arrester; viz., that if it cannot pass the laboratory tests it is sure to fail sooner or later on the line. The effect of resistance in an arrester circuit will be discussed again under the heading *Dielectric Spark Lag.*

There is another factor that must often be taken into account in equivalent needle gap tests of resistance, viz., the reactance. If a 100 kilovolts from a condenser is impressed on 10 feet of copper wire, each foot of wire will have a drop of about 10 kilovolts. Care must be taken to attach the needle-gap terminal directly to the resistance and not back on the leads. The resistance itself should be arranged in the form in which it is to be used. The ohmic drop can be separated from the reactance drop by the following method: take the equivalent needle gap of the resistance, then wind a heavy copper wire into the same general contour and take the equivalent needle gap of the wire.



In the equation, impedance drop $= \sqrt{(\text{ohmic drop})^2 + (\text{reactance drop})^2}$, the impedance drop is represented by the first value above and the reactance drop by the second. Using a known resistance, the writer has checked the above method and found the results approximately correct.

Dielectric Spark Lag. As soon as numerical values of voltage and resistance were used in the tests as described above, discrepancies began to arise. In the disruptive stroke tests the voltage represented by the equivalent needle gaps is always less than the initially impressed voltage. In Fig. 3b is given the logarithmic discharge curve of voltage across the *charging resistance* with time as the abscissa. With an impressed voltage of 150 kilovolts, the needle gap had to be set at a length which required only 65 kilovolts steadily applied to cause a spark. It seems reasonable to assume that the interval between 150 and 65 kilovolts on the curve, is a measure of the time it takes the needle gap to ionize and start to discharge. The time is 200 microseconds. The dielectric spark lag varies greatly with the materials of the dielectric and its condition. For example, oil has a dielectric spark lag much greater than air. Air has a dielectric spark lag which depends upon the nature of the light which falls on the electrodes. Hertz first called attention to the effect of the ultra-violet light from the spark at the machine gap assisting the needle gap to spark. In making arrester tests it is necessary to avoid these effects by placing a shield in such a position around the machine-gap *G* as to screen its light from the apparatus under test. The inductance of the arrester circuit adds a further time-element to the discharge. An arrester must be so placed in reference to the apparatus it is to protect that its dielectric spark lag is less than that of the insulation of the apparatus.

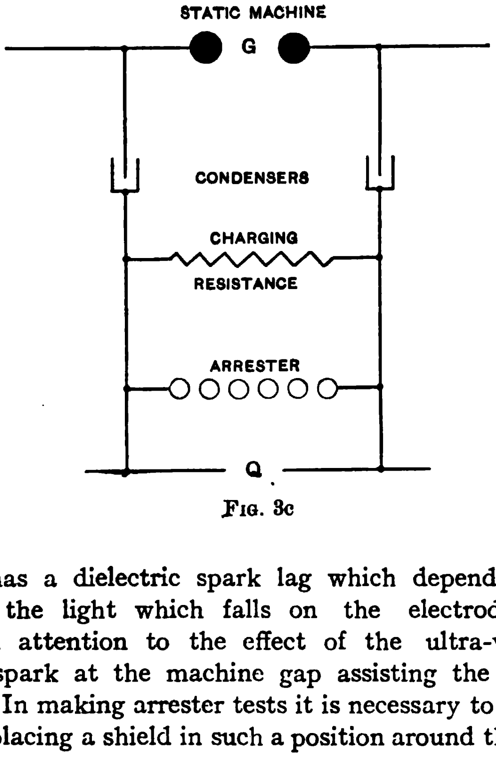


FIG. 3c

Following up the study of the dielectric spark lag we learned that the most dangerous condition of some types of arresters is, anomalously, not a heavy disruptive stroke but that stroke which will barely cause the arrester to spark. At this point the equivalent needle gap of the arrester is a maximum and the dielectric spark lag is also a maximum.

Fig. 3d shows the connections for test of a simple series of gaps between insulated brass cylinders and also shows the characteristic curves of the equivalent needle gap of a simple multigap set. It will be noticed that the equivalent needle gap curve (using increasing *G*-gap as abscissa) follows the equivalent needle gap of the charging resistance up to 3.2 in. then suddenly drops to a little more than a half the maximum value (1.8 in.) and retains this value sensibly, no matter how heavy the stroke. The arrester gaps do not begin to spark until the equivalent needle gap curve approaches its highest value. This test makes prominent two things: first, the necessity of designing the arrester to keep its equivalent needle gap within the safe value of the insulation it is designed to protect; secondly, the necessity of noting the value of impressed voltage that starts the arrester to sparking. The importance of the initial value of the impressed voltage and the dielectric spark lag will be more evident in tests of insulation to be described below.

If a resistance be added in series to the multigap the equivalent needle gap curve passes over a peak value as before and drops to about 50% of the peak value, but instead of maintaining this low value of equivalent needle gap, the curve gradually rises again as the quantity of electricity increases. So far as the lightning stroke itself is concerned, this experiment answers all questions regarding series resistance in lightning-arrester circuits. Any series impedance is detrimental. The heavier the stroke, the smaller must be the impedance. If the secondary line effects can be otherwise avoided, series resistance should be eliminated.

In practical testing there are a number of details which must be considered. The first and foremost is that the equivalent needle gap does not necessarily measure the puncture power. The electrostatic spark and the electromagnetic spark differ considerably in this respect. The recoil of a lightning-arrester choke-coil will under some circumstances give a long jump spark over a needle gap, but with solid or liquid insulations interposed the same potentials do apparently no harm. Any doubt regarding the puncture power of a stroke from the apparatus should be initially removed by placing the particular insulation that the arrester is to protect in the path of the discharge. If the insulation is punctured on the first stroke there can be no doubt regarding the puncture power. In this respect it is well to note that the energy or disruptive discharge must be derived from the condensers. In reducing the "proper frequency" of the circuit, care should be taken always to keep the increase in capacity greater than the increase in inductance.

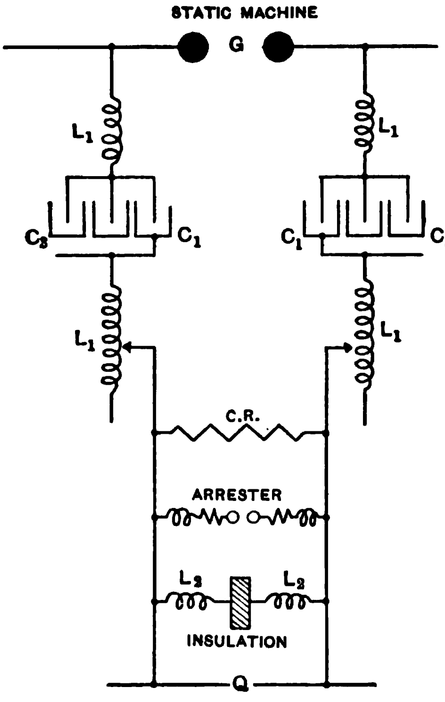


FIG. 3e

Fig. 3e shows a typical circuit involving most of the variable elements. In this circuit the impressed potential can be varied by the machine-gap *G*. A given length of machine-gap *G*, however, does not always represent the same voltage. Aside from the change in spark voltage due to pitting of the electrodes, collection of dust particles, ultra-violet rays, etc., there is another cause of variation which must either be guarded against or allowed for, viz., the frequency of stroke. After each stroke the atmosphere between the G-gap is left in a condition of ionization above the normal state. To return completely to a normal state, an interval between strokes of several seconds is sometimes necessary.

The proper frequency can be lowered by increasing the capacities ($C_1\, C_2\, C_3$) etc., and the inductances (L_1). The time of application of potential by varying the charging resistance (*C. R.*). The protection by the introduction of different types of arresters at (*L. A.*) each carrying its own inductance and resistance or artificial values to represent the line connections. The actual insulation to be protected should be introduced with an inductance L_2 to represent lightning-arrester choke-coils. An equivalent needle gap is desirable to give an indication of the factor of safety of the arrester, *i.e.*, the puncture voltage of the insulation divided by the equivalent needle gap voltage. The puncture power is represented by the combination of the machine-gap G, the capacities ($C_1\, C_2\, C_3$) etc., and the value of the charging resistance (*C. R.*). The *stroke frequency* is determined by the speed of rotation of the static machine. It is affected also by variation in the machine-gap G and the electrostatic capacities.

All the above quantities will affect the results of the tests. Variations in each of the factors would give an infinite number of combinations. Practically, the number of tests can be reduced to a reasonable value by using wide variations only of factors.

In making tests of equivalent needle gap by means of the disruptive stroke method it is sometimes necessary to have impressed on the arrester the normal voltage and generator frequency. Assuming that arc-extinguishing power is not the desideratum of the test, Fig. 3f shows a connection which gives all the static effects from the generator without risking the insulation of the generator or transformer by subjecting the insulation to the direct stroke from the static machine. The difference in circuits 3e and 3f lies in placing the charging resistance in series with the transformer leads and introducing a condenser, marked "auxiliary condenser," in the figure. This auxiliary condenser is designed to store the static energy which comes from the transformer, and introduce a low resistance circuit near the lightning arrester to permit of local surges taking place freely. It is absolutely essential, however, to make the capacity of the auxiliary condenser small as compared to the main condensers C_1 and C_2, or the potential of the disruptive stroke will be very sensibly diminished. The sole object in this application of the transformer is to put the arrester gaps near the line in the active condition in which they will be found in practice. The choke-coils and second lightning arrester $(L. A.)_2$ is added to the circuit as an extra safeguard.

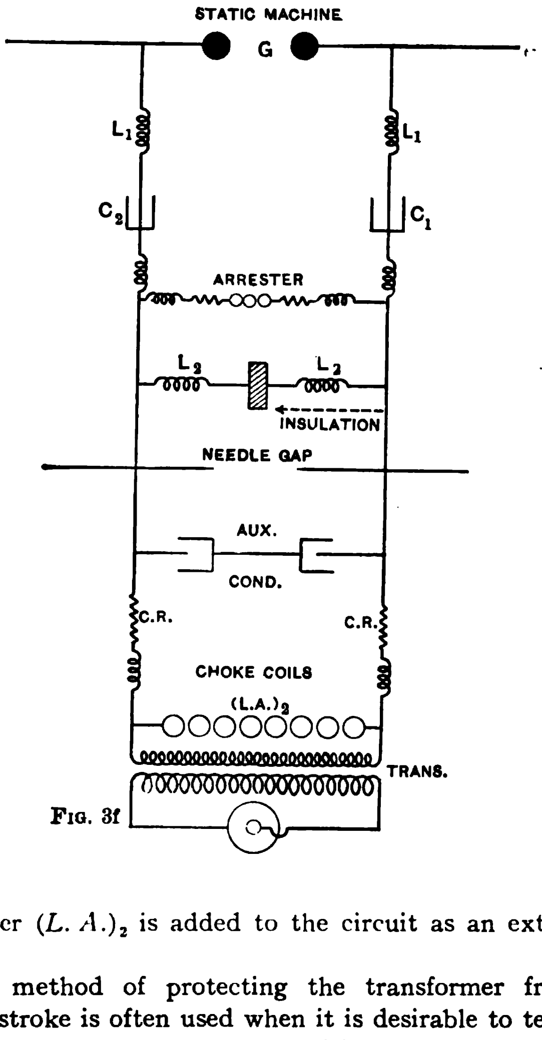


FIG. 3f

Another method of protecting the transformer from the disruptive stroke is often used when it is desirable to test some unknown arrester apparatus requiring alternating current. In this case the series resistances in the transformer circuit, as shown in Fig. 3f, must be removed. This method of sparking an arrester may be called the double-discharge method. The circuit connections are given in Fig. 3g. Charging resistance, if used, must be high relative to the voltage of the transformer.

Instead of charging resistance, needle points, or their equivalent in fine wire, may be placed in a suitable location and the condensers charged up through brush-discharge. One precaution necessary to take with this method is to provide a discharge spark powerful enough to extend in both directions across the arrester; otherwise one condenser will discharge around through the transformer.

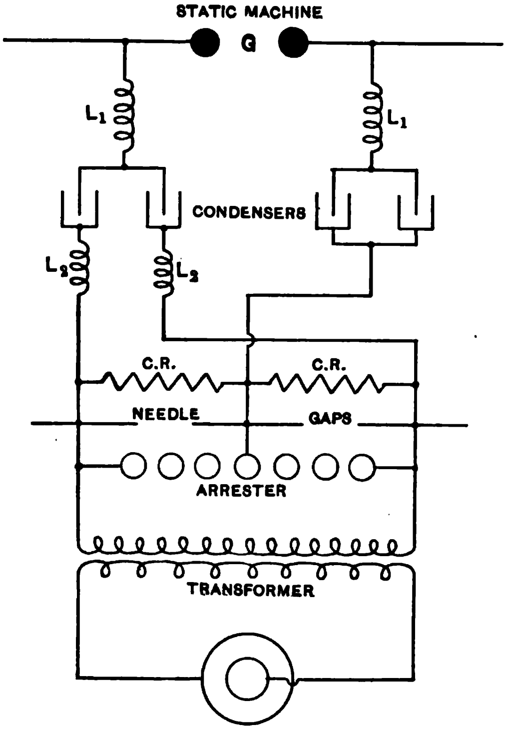


FIG. 3g

Following are two selected tests which show the characteristic behavior of two insulating materials under specified conditions. (a) Effect of a number of disruptive strokes on untreated pressboard insulation. Before the disruptive-stroke test was applied to this pressboard the normal frequency transformer test was applied and the dielectric strength determined. So long as the initial voltage of disruptive stroke was not greater than this value no damage resulted, but when the initial value of disruptive stroke was raised above this voltage it was only a matter of more or less strokes before the insulation was pierced—the greater the impressed voltage the less the number of strokes required to puncture.

The side of the problem of vital interest is the question of protection. Can we impress on an insulation a voltage that will puncture it by the first stroke if it is unprotected by an arrester, and then place an arrester in multiple and determine the degree of protection? Instead of an actual arrester a gap of variable value was used in the data given below. In the first test the insulation was placed between needle points and a needle gap was placed in parallel. In the second test the same pressboard was placed between 1.4-in. spheres and a sphere gap used in parallel as protection. These tests gave very definite results from which curves were drawn. I take from these curves the following values:

No. of strokes to puncture.	Needle-gap protector.	Sphere-gap protector.
1.	0.7 in.	0.5 in.
2.	0.65 in.	0.42 in.
7.	0.55 in.	0.31 in.
19.	0.50 in.	0.28 in.
60.	0.45 in.	0.18 in.
130.	0.40 in.	0.16 in.
∞	0.35 in.	0.15 in.

These tests show that for this kind of lightning stroke, and an arrester with an equivalent needle gap not greater than 0.35 in., this insulation would always be safe. If the equivalent needle gap curve for increasing potentials and quantity of electricity does not rise, *i.e.*, remains constant, then the arrester will be safe for all ranges of quantity and potential. The arrester must answer also the requirements of the other tests herein described before it can be placed in the class of a universal discharger.

These tests show also that an arrester may be giving apparent satisfaction and yet allow the insulation to be damaged to a certain extent by each stroke.

The arrester designer can thus state with considerable definiteness in most cases just how little insulation can be protected by a given arrester, and the problem is for the apparatus designer to install this insulation in the proper place in the apparatus. This part of the subject would not be complete without mention of the work done by Mr. W. S. Moody in the distribution of insulation in transformers. It has greatly lightened the arrester-man's burden.

There are methods of testing the risk of insulation in different parts of the windage that are subjected to lightning stroke, but the matter is too much involved to be treated in this paper.

(b) An experiment with an oil gap subjected to disruptive stroke which shows the effect of frequency of stroke. An oil gap between spheres had impressed upon it a disruptive potential of a value greater than the dielectric strength as determined by steadily applied potential, but applied for an interval of time less than the dielectric spark lag of the oil. Upon this oil gap was impressed different frequencies of strokes, with the following results:

Strokes per minute.	Punctures of the oil.	Per cent. puncture.
6.	0.	0.
34.	14.	41.
82.	58.	70.
111.	102.	92.

A plausible explanation of the effects found in this experiment seems to involve the *dielectric spark lag* and the *self-repairing quality* of the dielectric. Oil, like air, will repair the insulation if the potential is removed. The highest density of displacement current is naturally at the electrodes. Even if the oil lies between parallel plates, the seat of the energy must be the electrodes, and, assisted by the inevitable unevenness of surface, the phenomena of failure of the oil as a dielectric should start with the electrode. In the failure of the oil, the molecules are disrupted, some of the atoms appear as a gas and the remainder remain in the oil in the form of some hydrocarbon compound. If no arc follows, no visible deposit of carbon can be found in the oil. Since this gasification starts at the electrodes, and the potential is removed before a spark passes, it is necessary to wait but a short time and the oil has recovered its dielectric strength. If, on the other hand, a stroke follows before the effect of the preceding stroke has cleared away, each succeeding stroke will find an easy path in these semi-conducting layers near the electrodes.

The effect of frequency of stroke is very prominent in this experiment, in spite of the fact that the maximum potential between machine electrodes (the *G*-gap) is less at a frequency of 111 strokes per minute than it is at 6 strokes per minute. The explanation of this difference in potential is made in somewhat the same way as above—the air has not time between strokes fully to recover its normal dielectric strength.

Fourth Test: The fourth method of test is that of the inductorium or Thompson transformer, a typical circuit of which is shown in Fig. 4. The inductorium circuit is shown inside the rectangular lines. This test can be made to reproduce fairly well the condition of a transmission line with a phase grounded through an arc.

Fifth Test: Half-wave Test. This is a test to which no attention has been given, yet it is of importance in transmission work. A typical half-wave testing circuit is shown in Fig. 5.

The test has for its object the reproduction of low-frequency surge conditions. In introducing this method of test the writer had in mind an incident of a test he made two years ago on a 33-kilovolt, 50-mile transmission line. The experimental work was done on an idle parallel line with separate generators. Induction between lines carried a momentary surge to the working line, and, due to a faulty relay, the oil switches on the main line were opened at the power house. The experimental line was unaffected by the surge. Thirty miles from the power house a transformer jumped an arc 9 in. across its leads. Since the power was cut off, the transformer was uninjured. This seems to have been a case of recoil of the line and transformer, and the spark was transformed into an arc by the energy of the momentum of the sub-station synchronous converters.

Sixth Test: The Arc-extinguishing Quality. Anyone can design an arrester that will, in general, protect against lightning stroke. The difficulty lies in combining the protective quality with that of the quiet suppression of the arc which usually follows a lightning stroke over an arrester. The arc does not always follow, for reasons that will be given below. The arrester-man holds the unenviable classical position between the devil and the deep sea. If he goes too high with the number of units or resistance he gets a shock with a punctured transformer; if the number of units and resistance is too low, it is a burned-up arrester. In either case the transmission system is usually shut down.

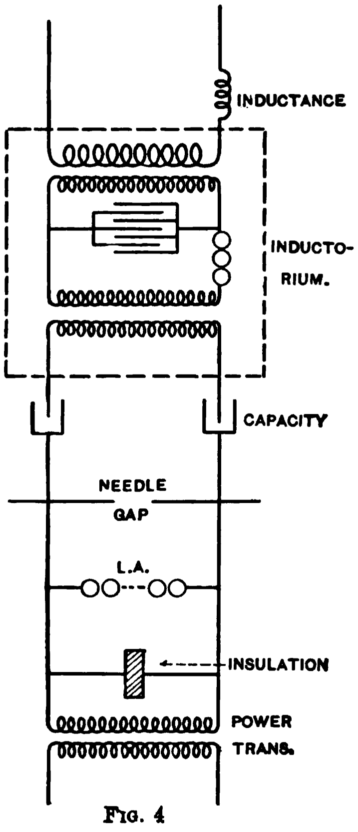


FIG. 4

The usual method of suppressing the dynamic arc is by means of a number of series gaps between brass cylinders. In the light of recent work the name non-arcing metal applied to the brass is inappropriate. Dr. C. P. Steinmetz has pointed out that it is a rectifying effect. The rectifying power depends upon the difficulty met in reversing the arc stream. Once established in either direction the current flows without any appreciable difficulty. The three principal materials in the order of their rectifying power, are zinc, magnetite, and mercury. Zinc, however, is not the best material to use in an arrester. This is due principally to its low-melting temperature. In a lightning arrester the rectifying quality is obliterated by the splashing of the molten metal across the air-gap. There is a very definite amount of energy that can be expended in each gap during a half cycle of the generator before the metal will splash across the gap and short circuit the cylinders. This energy is easily measured with a ballistic wattmeter. In early developments of power when the generator capacity was small and regulation poor the simple multigap arrester worked very satisfactorily, due to the drop in potential and the limited energy. With the increase in the kilowatt capacity it was necessary to increase either the number of gaps or add resistance

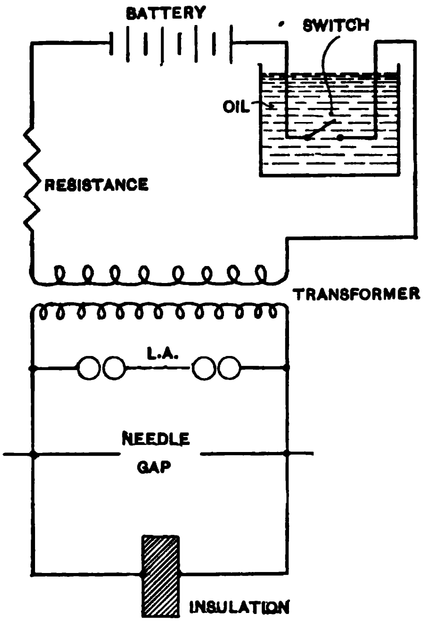


Fig. 5

to limit the expenditure of energy at each gap to the rectifying limit, or rather to the splashing point.

It is not the object to discuss the multigap arrester in this part of the paper, but only to point out the essential conditions attending rectification and give a method of test of the same.

In testing arc-extinguishing quality the first requisite is sufficient power to sustain an arc over the simple multigaps used. The second, is a ballistic wattmeter to measure the energy lost per stroke. The third requisite is a suitable set of resistances to use in parallel or series with the multigaps. The fourth requisite is a synchronous switch. This synchronous switch consists of a rotating insulating arm carrying a conductor which sets off the static spark at any desired point of the electromotive-force wave. This arm is carried by either the generator shaft or an auxiliary synchronous motor.

By this means we have studied the discharge which follows the static spark. Starting with the zero value of the electromotive force no current follows the spark. With twelve gaps in series on a 2 400-volt circuit it is possible to move back up the electromotive-force wave to a considerable percentage of the maximum value before the line current begins to follow the spark.

This is a point on the curve as definite as shown in the oscillograms of current and electromotive force in an alternating-current arc made by M. A. Blondel in 1898. As shown in these oscillograms, the current is extinguished before the electromotive force reaches its zero value. Since the current at this point is extinguished as soon as established, the energy lost will be so slight that the cylinders will be able to conduct the heat away and radiate it between strokes.

If, however, the synchronous switch is carried still farther back on the electromotive-force wave, the current will be of correspondingly greater intensity and duration. The maximum expenditure of energy will take place when the point on the rising part of the electromotive force wave is reached where the spark just causes an arc. The current then is on the longest time possible in the half wave. Any point lower on the electromotive force wave allows a spark to pass without an arc following. These tests indicate why some arresters have been satisfactory for long periods and finally burn up. It is a case of the law of chance.

There is another piece of apparatus that is desirable to have, viz., an oscillograph to indicate whether the arc is extinguished at the end of the first half cycle or not. Since taking an oscillogram for each stroke involves considerable time and some expense, a substitute can be made of some form of apparatus utilizing the difference in the electrochemical effect of a direct current and an alternating current. If the ballistic wattmeter deflection has once been noted when the duration of current was known to be but a half cycle, neither of the devices above are really necessary to show whether the current carries over more than a halfcycle.

Another factor affecting the arc-extinguishing quality is the frequency of stroke. Two rapidly succeeding strokes will do more damage and constitute a greater risk of permanently establishing an arc than a dozen or more strokes at intervals of several seconds. The required severity of the test is a matter of judgment. It would seem to be sufficiently severe to demand that the multigap arrester extinguish a double stroke at least once without excessive damage to the arrester, and that the arrester should have an endurance of perhaps a thousand strokes taken with such an interval between strokes as to allow the cylinders to radiate the heat energy from the arc.

In making developments it is expensive to burn up an arrester each time the inside limit of arc-extinguishing power is reached, consequently a series of tests were made using fuses of increasing sizes in series until a limit was reached such that the arrester was put out of commission. A fuse of less area was chosen that would " blow " when the arc persisted over more than a half cycle; it was an indicator of molten metal splashing and the danger point. During the short interval of a half cycle the heating is confined to the surface; and although the cylinders would be damaged if left on the circuit they are not seriously damaged when the fuse cuts off the current.

In closing this paper the writer wishes to take this, the first opportunity of expressing his grateful indebtedness to the assistance received (somewhat directly and greatly indirectly) from three engineers with whom he has served as assistant in the past few years, namely, Dr. F. A. C. Perrine, M. Andre Blondel, and Dr. C. P. Steinmetz.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

PROTECTIVE APPARATUS FOR LIGHTNING AND STATIC STRAINS.

BY H. C. WIRT.

There seems to be a diversity of opinion in the operation of transmission systems regarding lightning effects A committee of the National Electric Light Association made a report to the association last year regarding the operation of protective devices. The committee has been continued and will make another report this year. This indicates that electric service is interrupted by lightning, and a desire for improvement in protective devices. The published accounts of protective devices usually contain little regarding actual operating results. Each account is generally a description of the arrester and the principle of operation as regards extinguishing the dynamic arc which follows the lightning discharge. Information that would be of great value to operating engineers is the result secured from arresters in actual service. But little has been published in this regard.

The protection of high-tension transmission lines is particularly difficult, and results show that at times the best known types of arresters for this work fail to protect the system. For the protection of these lines the most common types of arresters are the following:

1. Multigap with series resistance;
2. Multigap with shunt and series resistance;
3. Multigap without resistance;
4. Horn-gap lightning arresters without resistance;
5. Horn-gap with series resistance;
6. Two horn-gaps in series to ground with resistance shunting one of the gaps.

7. Water stream from line to ground;
8. Overhead grounded wire.

It will be seen from the above list of lightning-arresters, that all make use of resistance, except the multigap without resistance (arrester No. 3), and the horn-gap without resistance (arrester No. 4). The writer has had experience extending over a period of 16 years, with several types of arresters. Two years ago it became important to make a study of the entire situation to see along what lines it would be promising to work to develop an arrester of an improved type. The experience gained during recent years was a basis for the investigation.

In the study of this problem too much weight should not be given to laboratory tests; for the reason that it is practically impossible to approximate the condition of a transmission system during a lightning storm. In the past, some arresters which have tested out well in the laboratory have failed in actual operation. The laboratory can be used for the study of problems, but the actual confirmation of results should be secured by trial installations on several transmission systems. We should not, therefore, jump at conclusions drawn from laboratory tests.

The effect of lightning discharges depends upon the frequency, and the volume of current. In the case of those arresters using series resistance it is apparent that the voltage rise around the resistance may be considerable, depending upon the amount of current passed; and this voltage rise is independent of the retardation afforded by the so-called skin effect. My observation has been that arresters employing series resistance sometimes fail to protect the apparatus. I believe this is due to the rise of voltage around the resistance, together with the skin effect. By making the resistance low, the rise of voltage due to the resistance can be reduced. Whether an arrester of extremely low resistance will protect remains to be proved.

Knowing this effect of series resistance, in developing a new arrester it was natural to study the operation of multigap arresters without resistance. This type of arrester has been very generally used for 2 200-volt circuits with six gaps to ground, making twelve gaps from line to line. Reports obtained from the operation of these arresters show that they occasionally short circuit and hold the dynamic arc, so that fuses of even 100 amperes capacity placed in circuit with them have been blown during the discharge. These arresters were made of non-arcing metal.

From these reports it is evident that some changes in the design of this arrester had to be made to make it satisfactory as regards limiting the dynamic current. The short-circuiting effect can be decreased by increasing the number of gaps at the expense of making the arrester less effective as regards protection.

It is known that disturbances are caused on a system by allowing too large a flow of current across arresters; therefore, the requirement that an arrester should take a limited amount of dynamic current naturally suggests itself. The writer considered that a three-ampere fuse wire placed in series with the arrester should not be melted on the discharge of a static machine across the gaps to start the dynamic arc. With this requirement in view, tests were made to see how many gaps would have to be placed in series properly to limit the current. During the 2 200-volt test, gap after gap was added, until 48 gaps from line to line were used before the current was properly limited. A consideration of the expense and size of this arrester showed immediately that it would be uncommercial.

Experiments were then conducted to see how the number of gaps could be reduced by the use of resistance in shunt to some of the cylinders. It was found that nine gaps, six of them shunted by carborundum resistance, would limit the current to the proper amount so as not to blow a three-ampere fuse. Usually there will be two such combinations in series, giving 18 gaps from line to line with 12 of these shunted by resistance. Making further tests on this arrester, it was found that low-voltage discharges from a Leyden jar would pass through the series gaps and resistance, but high-voltage discharges would pass through all the gaps, thus producing an arrester which allows a direct discharge across the gaps to ground without taking too large a dynamic current. It is realized that the lightning discharge itself may give a spark across the gaps which will allow greater dynamic current to flow than during the Leyden-jar test. The amount of lightning current can be determined only by actual tests on lines. Five hundred of the multigap arresters with shunt resistances for 2 200-volt circuits were placed in service last season and operated practically without trouble.

As lines may become grounded, cutting out half the protection from line to line, to withhold the dynamic current it is desirable to make a single-pole arrester stand the full voltage of the circuit. In making tests on non-arcing qualities, two single-pole arresters should be connected in series and these connected directly across the circuit, so that the full voltage will be applied at the terminals of the combination. It is usual to test arresters by discharging Leyden jars across the gaps and allowing the dynamic current to follow. If the arrester is unable to break the dynamic arc it will soon burn up or blow fuses, as a short circuit will be caused.

In a test of this kind a large-capacity generator should be used to represent commercial conditions. The following test made in this manner may be of interest. Arrester (Figs. 1 to 3) consists of a number of carbon discs separated by sheet mica.

FIG. 1.

The combination shown is what is regularly intended for 2 200-volt circuits. Upon the discharge of the Leyden jar the arrester short circuited, arcs being driven out from the discs with great violence. The capacity of the generator was 400 kw., and arresters were tested at a point about two miles from the central station. Arrester (Figs. 4 and 5) is the standard non-arcing metal arrester with 6 gaps from line to ground, giving 12 gaps from line to line. This arrester blew fuses of 50-ampere capacity. Arrester (Fig. 6) is the multigap arrester with a carborundum rod shunting some of the gaps. The arrester has 9 gaps from line to ground, 6 of them shunted by resistance, giving 18 gaps from line to line including 12 gaps shunted by resistance. This arrester did not blow 3-ampere capacity fuses. Arrester (Fig. 7) is the usual type designed for 2 200 volts, having two series gaps with series resistance. It is noticeable from the photographs that the spark between gaps is much smaller in this arrester than in the multigap with shunt resistance. In other words, the dynamic current is limited by the resistance, but this resistance may also sometimes unduly limit the flow of the lightning current. In this connection a few cases have been reported in the use of the arresters as line arresters where the lightning has jumped from the terminals of the carborundum rods to the iron boxes, particularly where the line wires enter the box. During the season a few arresters have been reported as operating in this manner. The lightning jumped from the terminals to the iron box, a distance of about $\frac{3}{4}$ in. on each side, making a short circuit from line to line in preference to going through the carborundum rod and the ground connection to ground, or from one carborundum rod through the gaps to the other carborundum rod and line. This can only happen when the potential built up across the carborundum rod becomes high, whether skin effect enters in or not due to the resistance of the rod when a large current is flowing.

FIG. 2.

A consideration of these points has led to the development of the multigap shunted-resistance type of arrester. If the bad effect of series resistance is admitted, all arresters employing this method of limiting the dynamic current—such as water streams, permanent resistance of any kind from line to line, series resistance and the solenoid switch arrester which has been used somewhat for 2 200-volt circuits in recent years—will be ruled out of consideration. The solenoid-switch type of arrester is arranged so that upon the passage of the lightning stroke followed by the dynamic current, the solenoid is lifted and a momentary air break is made in the circuit. In order to limit the dynamic current, series resistance is employed together with resistance around the terminals of the magnet to shunt the reactance of the magnet, as well as protect the magnet itself from the lightning stroke. Series resistance arresters will no doubt take care of many effects of low voltage and low frequency, but my observation has been that they will not take care of all effects. Further proof of this can be cited by the observation of a 12 000-volt, three-phase arrester which happened to be installed near channel-irons which were grounded. When the lightning stroke came into the station, an arc jumped from the terminals of the arrester a distance of 4 in. from each phase to ground in preference to passing through the arrester to the ground wire. This arrester had multigaps and series resistance.

Fig. 3.

In connection with the protection of high-voltage transmission circuits the new points that have developed in the past two years are the following:

First, the effect of a ground on a three-phase line with ungrounded neutral. It has been found in practice that when a ground connection is made on one of the three phase wires, arresters in the station have arced over as far as the multiplex connection, *i.e*, the circuit being from line to line, and, this voltage being maintained continuously, the arrester is unable on account of its close adjustment to break the dynamic arc, so that the cylinders are welded together and the resistance destroyed. This result led to experimental investigation and it was found that approximately double potential, as determined by means of spark gaps, was secured from a line grounded in the above manner. At first it was thought that the line effects were the cause of this high voltage, but the same results have been secured from a single transformer and even from a high potential testing transformer. Apparently, the voltage is of such high frequency that it is not shown by standard types of voltmeters operated from secondary of transformer, known as ratio voltmeter, or by electrostatic voltmeter, and was discovered by means of a spark gap. It was found that this voltage was approximately double the working voltage. It is evident, therefore, that when lines become grounded in this manner the arrester has to stand approximately double potential, so, therefore, it may be desirable if possible to adjust the arresters so that they will not arc together when this ground is made. The writer believes that this effect is not generally understood by operating engineers.

FIG. 4.

If the arrester is set up high enough so that when a ground occurs the static voltage will not go over it, then the adjustment may be so close to what the insulation will stand that there is little chance to protect. If the insulation factor was placed much higher there would be greater opportunity for the adjustment of the arresters.

A consideration of the above point brings up immediately for discussion the question of grounded Y systems as compared with systems operated with ungrounded Y, or delta connected. With the grounded Y system the static voltages are not created when a ground occurs; for in such a case an absolute short circuit is made and the circuit breaker or other protective device opens the line. The disadvantage of a grounded Y circuit is that any ground, unless high resistance is interposed between the ground and the Y at the station, will shut off the circuit by opening the circuit breaker; whereas there have been cases where an ungrounded system, either Y or delta connected, has continued to operate with one line of the ground. In discussing the above points with operating engineers they seem to be about equally divided in their opinions as regards one practice or the other. The systems in California are quite generally operated with grounded Y, but in that locality rain and lightning storms are very infrequent. Arresters go through entire seasons without a discharge over them, so that I think we should not use that locality as an example of what would occur in Eastern localities where thunder storms are very frequent. Plants around Salt Lake City are operating some

FIG. 5.

in one way and some in another, and several of the operating engineers who are using both grounded Y and delta connected systems, feel that the delta system is preferable and will use it in future extensions. Another important point in connection with lightning protection is the effect of short circuits on the system. The writer had placed at his disposal for testing purposes a 13 000-volt system, five miles in length. Two short circuits were made, at different times, and each time apparatus burned out on the system. The arresters on the system were not of the improved type with the best adjustment. These experiments are to be continued, as a system ought to operate, if possible, so that short circuits which are likely to occur will not burn out apparatus. In actual service short circuits have occurred in some cases with disastrous results. Reports have reached me regarding short circuits caused on other systems which have not burned out apparatus.

FIG. 6.

In developing the design of the shunt resistance type of arrester for high tension transmission systems, the following features were given consideration:

In order to limit the dynamic current to proper value a very large number of gaps had to be used. In the New Milford installation, where the arresters were used without the shunt resistance, 672 gaps were placed in series from line to line and from line to ground, as it was thought that this number would be required to prevent a short circuit on the system. It was discovered on test that the Leyden-jar discharge would go over a much greater total distance in individual gaps than over a single-gap, that the cylinders had very great electrostatic capacity and that the breakdown point varied as regards the size of cylinders, width of gaps, etc.

The theory of the operation of this arrester is that the cylinders are charged up electrostatically with sufficient voltage so that the gaps are broken down in succession, passing the charge along from cylinder to cylinder and discharging the whole series practically instantaneously. It was found during the tests that it made little difference whether the shunt resistance was connected or not, this test being made with Leyden jars. These laboratory tests have shown that the low voltage moderate current discharges go through the series gaps and resistance and the large current high voltage discharges through all the gaps. The exact adjustment of series and shunt gaps had to be determined by actual service tests, and much data is being accumulated at the present time on this point.

FIG. 7.

At first the arresters were installed without any resistance, and even in this condition gave a remarkable improvement in operation over the arresters of older type having distributed series resistance. No arrester in any sub-station held the dynamic arc, and the arresters at the generating station held the dynamic arc only three times. On account of this experience the shunt resistances have been added, and several storms have been weathered successfully.

NON-ARCING METAL.

The character of the metal used has much to do with the amount of dynamic current that will pass through the arrester after the static discharge. Cylinders of uniform size were constructed of many different metals and alloys, including the so-called non-arcing metal now on the market. Tests were made by operating an arrester with 12 gaps on a 2 300-volt circuit, discharging Leyden jars across the gap while the terminals of the arrester were connected to the live line. Fuses of varying capacity were placed in series so as to indicate the smallest fuse that could be used without melting, thereby giving a fair measure of the non-arcing property of the metal. Cylinders of aluminum, of zinc and of alloys of zinc fused together readily, whereas cylinders made of other compositions operated much better. With the best alloy, a reduction of 10% in the number of gaps could be made compared to the number required when ordinary brass rod was used for the cylinders with the same dynamic current; the value of the non-arcing metal is equivalent to 10% of the number of gaps used. This new alloy was also found to be about 5% better than non-arcing metals previously used in arresters. An amalgam of mercury was tried, but with poor results.

Another important point was developed, that is, that the cylinders should be well insulated, as an arrester in which the cylinders are mounted on marble had an excessive breakdown, as shown by the equivalent needle gap test, whereas the same number and arrangement of cylinders mounted on porcelain bases had a low breakdown.

As these cylinders when arranged in a straight line with 600 gaps for 33 000-volt circuit, would give an arrangement approximately 45 ft. long—too large to place in the station—the zig-zag arrangement of cylinders was adopted. All equivalent needle gap tests made on arresters as well as service tests, have been with the cylinders arranged in this manner, and the arrangement does not seem to introduce objectionable reactance. In fact, theoretical consideration of the design has shown that one row equalizes another so that there is less reactance than if the cylinders were in a straight line. For the sake of convenience and compactness the " V " form of arrester unit has been adopted, no connectors between units being required, as with these units a gap of proper width is formed between the last cylinder of a given unit and the first cylinder of the next unit of the series by merely placing the gaps side by side, thus doing away with connectors. This type of arrester for 2 200 volts is shown in Fig. 8, and for 35 000 volts in Fig. 9. There is an advantage in the grounded **Y** system in the arrangement of gaps compared with the delta system, as the arresters can be designed for 58% of the voltage between line and ground, thus giving a lower breakdown from line to ground than with the delta system. The arresters for the grounded **Y** system are arranged with multiplex connection, and a small number of units is placed between multiplex and ground, so that telltale papers can be used to indicate the path of the discharge.

USE OF REACTIVE COILS.

There has always been a discussion among engineers as regards the actual utility of reactive coils placed between the lightning arresters and the generators or apparatus to be protected. In a recent installation where very effective reactive coils having a large number of turns were used, the discharge took place on the apparatus side of the reactive coils, from line to line; so that in this case the reactive coils undoubtedly created opposition to the relief of the system, as the static disturbance, originating on the machine side, would have had to pass through the reactive coils to reach the arrester. In spite of the use of reactive coils, there have been a large number of installations where static sparks have jumped across the windings of generators and transformers. The static strains are undoubtedly of both high and low frequency, as Figs. 10 and 11, showing the burning out of two potential transformers, shows clearly that the breakdown from the primary to the grounded secondary occurred on various coils located at intermediate points in the winding. For low frequency effects, reactive coils will not be of any great benefit, but for high frequency effects they may be very desirable and for these effects comparatively few turns of wire should be sufficient. In many installations where air insulated reactive coils of comparatively few turns have been used, beneficial results have been noted. In one case before the installation of these coils, static sparks were continually jumping from con-

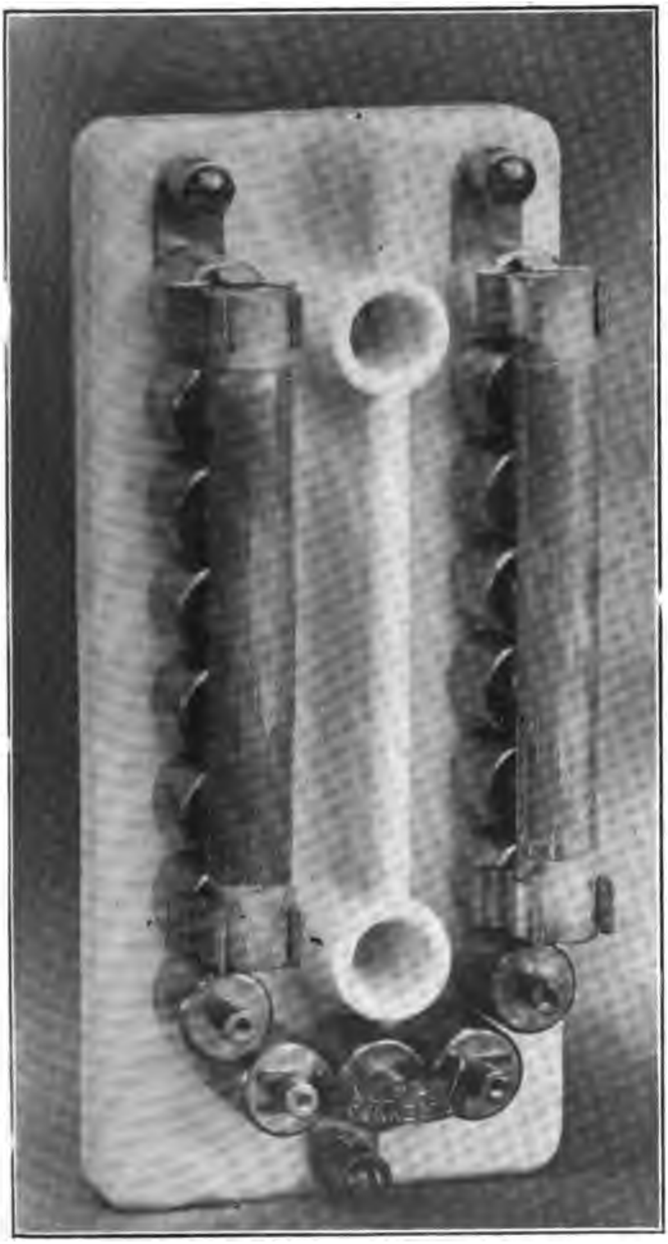


FIG. 8.—2 000-volt, double-pole, form-U lightning arrester for station work.

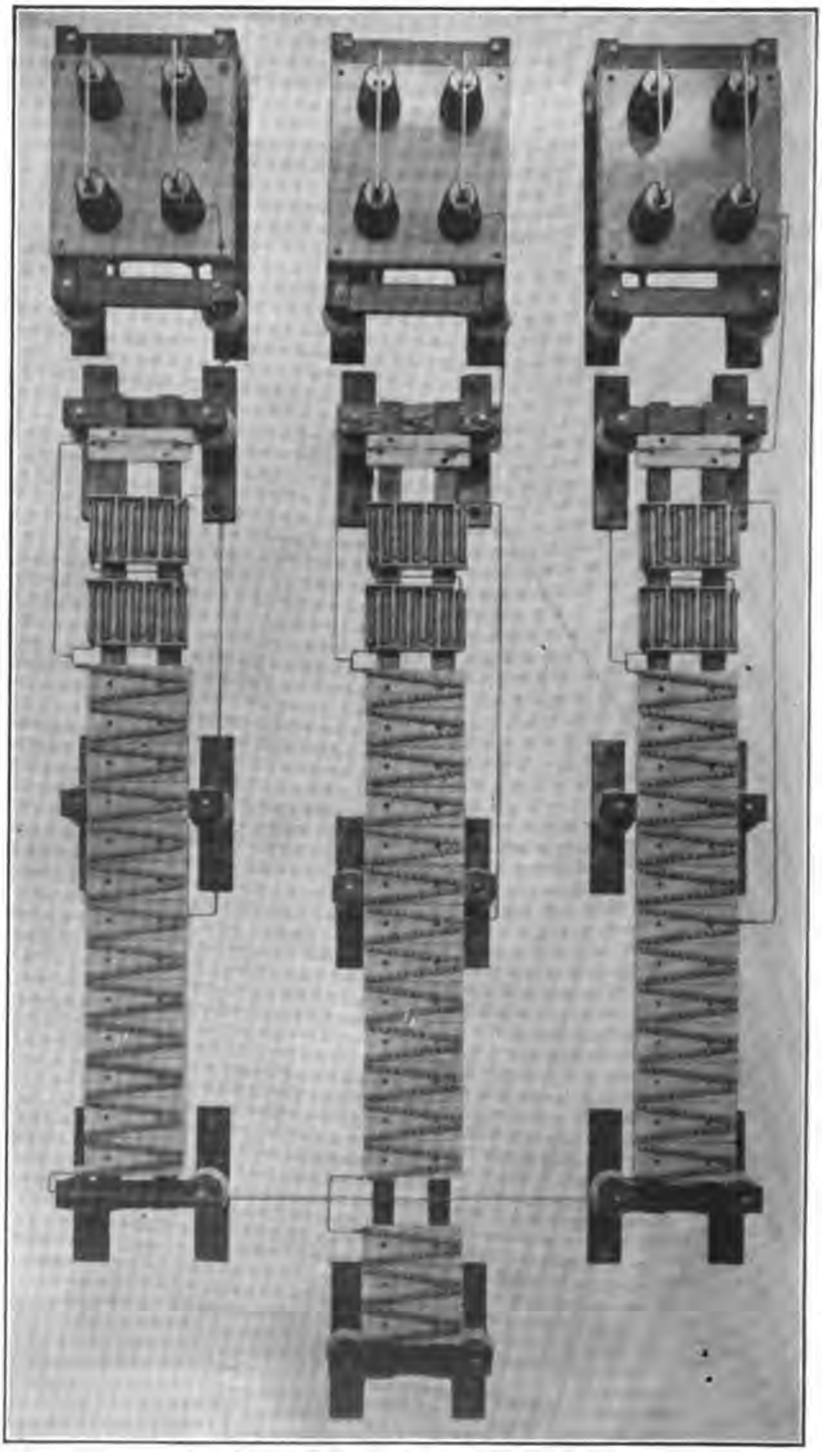


Fig. 9.—3 500-volt, three-phase, form-V multiplex lightning-arrester with double-blade disconnecting switches for Y-connected neutral, grounded circuits.

ductors to the iron frame work, but after the installation of these coils with practically no other change in the installation the jumping of static sparks has ceased.

Until recently the common idea as regards the effects that are taking place in a transmission system during lightning storms has been that a high potential wave has come from the outside circuit usually a considerable distance, to the station

FIG. 10.

Fig. 11

and discharged to ground either through the apparatus or through the lightning arresters, and that by the interposition of a reactive coil between the lightning arresters and apparatus the lightning discharge has been repelled to ground through the arrester. According to recent experience this idea of the effects in a system is incomplete and primitive. There is good proof to support the view that considerable effect is exerted by the electrostatic capacity of the entire transmission system—not only from lines to ground but also from line to line, as shown by the discharges through multiplex arresters from line to line without any discharge to earth. At all times during the operation of a system there is a condenser effect, and the line voltages resulting therefrom are apt to be greatly above the voltage of the generator. The lightning disturbance charges up the system electrostatically and the excessive aggregate voltage causes a discharge to pass. This discharge may occur on the lines outside a station—from line to line over cross arms —for example, making a short circuit and causing a surge of dynamic current which in turn breaks down apparatus at the station; so, that although there would appear to be only a remote connection between the high voltage manifestation in the apparatus and the short circuit on the line, one is really a consequence of the other; or the discharge may take place from line to ground, thereby setting up high static stresses between line and line in the station, or anywhere else in the system, and giving rise to high voltage oscillations.

From the above considerations it is apparent that an arrester must be able to take disturbances of both high and low frequency and of considerable current capacity as well. It is believed that the shunt resistance type of arrester is an advance in the art, inasmuch as it affords effective protection against the disturbances of widely varying character.

POLE LINE PROTECTION OVERHEAD GROUNDED WIRE.

Mr. J. B. Foote, General Superintendent of the Commonwealth Power Co., operating a very extensive system around Jackson, Mich., at 40 000 volts potential, has furnished the following information in reference to the protection afforded by the overhead grounded wire, the system being operated practically without lightning arresters at the stations:

The troubles experienced on the system during the season of 1905 up to August 5, were as follows:

May 4—Lightning came into the Jackson sub-station and burnt off the leads on the step-down transformer.

May 5—At Albion sub-station lightning entered and burnt off leads of transformer just above the oil.

May 11—Lightning struck the line and shut the rotary down for a few minutes but did no damage to apparatus.

June 19—Lightning struck the line and burnt leads off the two transformers at Battle Creek.

July 19—Lightning struck the line and burnt transformer out at Kalamazoo.

On June 29, the following information was furnished: " We have had two very severe storms in each of which we lost several rotary converters and burnt the high tension leads off the transformer just above the oil. We have had no damage whatever to our pole lines nor have we had any damage to our poles or cross arms since we installed the ground wire. The ground wire does not seem to afford any protection to the station apparatus where the lightning strikes in the immediate vicinity of the plant, but does afford a very thorough protection to the poles and other supports."

August 19—Service interrupted for two minutes during lightning storm, but resulted in no material damage to apparatus and none to the pole line.

Many cases have been reported where poles have been shattered by lightning. On the other hand several large transmission companies have operated throughout the season without losing any poles, but as an interruption of service is extremely objectionable to a large transmission company, some protection against the shattering of poles by lightning is much to be desired.

Poles have been well protected by an overhead grounded wire. Another form of protection would be to run a wire down the side of the pole, from the top to a ground plate beneath the pole. Every fifth pole should be grounded in this manner.

A photograph of a pole shattered by lightning on the lines of a transmission company is shown in Fig. 12.

Another accident is shown in Fig. 13 furnished by the Spring River Power Co., Joplin, Mo. The two lower wires shown are telephone wires, the next upper wire is a ground wire grounded every fourth pole. Mr. G. E. Hayler, Superintendent of the Spring River Power Co., has furnished me the following description of the condition of his line after it was struck by lightning:

By referring to the sketch you will note the construction of our line, the two lower wires being telephone wires and located approximately twenty feet from the ground. The next upper wire is a ground wire grounded at every fourth pole and approximately five feet above the telephone wires. Line wires are spaced 42 inches apart and are of No. 4 hard drawn copper supported on Locke No. 311 insulators.

You will note that in all probability lightning struck pole No. 90 totally destroying the top of same and leaving only a stub extending as far as the telephone wires. The cross arm was torn from the pole and hung by its undamaged insulator to the south wire. The wires were not burned in two at this pole, although both of the other insulators were totally destroyed. Pole No. 94 had one insulator broken. Poles between 94 and 90 were more or less slivered, but otherwise not damaged. Poles No. 89 and 88 also had slivered tops, otherwise not damaged. Pole No. 87 was evidently the breaking point of the arcs and possibly this pole received a lightning discharge. At any rate, the pole is quite seriously damaged on top. The top insulator was shattered and the line wire burned in two at this point, the line wire, of course, falling to ground on both sides. On pole No. 60 there are evidences that the current jumped from the insulator to the cross arm, thence down the pole to the ground wire.

Fig. 12.

I am at somewhat of a loss to explain just why the wire burned in two on pole No. 87. There is not sufficient evidence to warrant the belief that an arc was maintained at this point for any period of time.

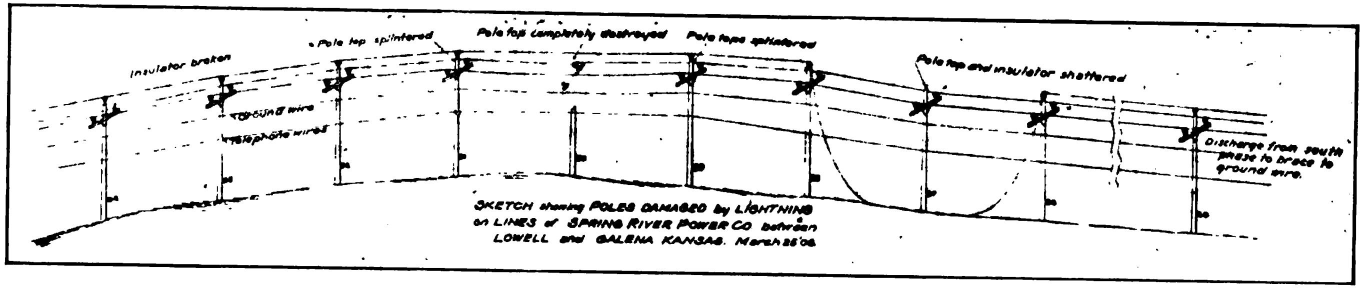

Insulator broken
Pole top splintered
Ground wire
Telephone wires
Pole top completely destroyed
Pole tops splintered
Pole top and insulator shattered
Discharge from south phase to brace to ground wire.
SKETCH showing POLES DAMAGED by LIGHTNING on LINES of SPRING RIVER POWER Co. between LOWELL and GALENA KANSAS. March 25'06.

FIG. 13.

Had this been the case the pole would have been more seriously burned than it is. We have had several cases previous to this experience where poles have been burned off due to lightning discharges starting an arc across the phases. In every case we have had wires burned in two but in each case the point of breakage has been on a pole which showed signs of a violent arc continuing for some length of time.

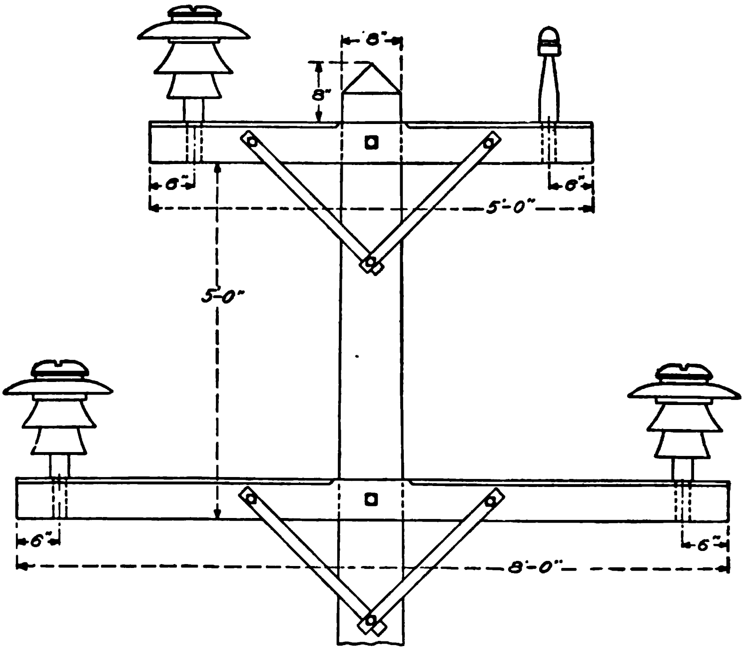
I regret to say in this connection, that the lightning arrester records made on the night that this accident happened are exceedingly incomplete. Our line patrolman seemed to be incapable of understanding the necessity for keeping these records as they should be kept, with the result that after the storm we found that the records were practically valueless on account of their having mixed the shunt and series papers. As a matter of fact, we did get a very decided discharge through the shunt gaps at the Lowell station. This is evidenced by a set of three papers which I am positive were in their proper position. It might be interesting to add that we obtained very marked discharges on this same occasion across our arresters, located about eighteen or twenty miles from the power station.

In reference to the matter of ground wires, it is my opinion that a good ground wire is an excellent protection against lightning. I am convinced, however, that this wire should be placed on top of the pole above everything in order that it may take the brunt of the lightning discharge. Your suggestion as to ground wire running to the top of every fourth pole is a very good one, but I believe the better plan to be to string a wire the entire length of the line and ground it at least at every fourth pole.

The Commonwealth Company two months ago completed the installation of 100 miles of 66 000 volt transmission lines, constructed as shown by Fig. 14. The construction is standard for both 40 000 and 66 000 volt lines. The insulator for the grounded overhead wire is clearly shown. The grounded wire consists of a No. 4 B W G double galvanized solid iron wire, grounded at every fourth pole by a piece of the same wire stapled to the pole and terminating in a flat pan-cake coil which is stapled to the bottom of the pole before the pole is set into the ground.

An interesting test was made on the lines of the Butte (Mont.) Transmission Company by providing the ground connections of the overhead wire with switches. Tests showed that the severity of the discharges over the arresters in the station with the switches open was very much greater than with switches closed, apparently indicating that the grounded wire reduced the voltage strain at the station.

Sufficient data has been secured to show that without an overhead grounded wire, or a ground wire running down every fourth or fifth pole, poles are liable to be struck sometimes and service interrupted, so that in all large undertakings it would seem to be advisable to use some sort of pole protection. The data also seems to indicate, however, that this arrangement will not fully prevent the burning out of apparatus, and additional protective devices will have to be used in connection with apparatus.



Commonwealth Power Co's
Standard Pole Top Construction
40000 and 60000 Volt Transmission

FIG. 14.

LINE LIGHTNING-ARRESTERS.

It has not been the practice in high tension transmission systems to install arresters on the line, although this is a common practice with 2 200-volt systems.

In connection with the New Milford installation, after lines had been struck by lightning and the wires severed, a line lightning arrester was installed so that the effect of this might be noted. During storms these arresters discharge as freely as the arresters at the station or sub-station. As this indicates abnormal pressures on the line, it is undoubtedly good practice to use line lightning arresters at points on the lines greatly exposed to lightning effects. In order to follow this practice safely, extremely reliable arresters must be used in all cases where a watchman is not constantly employed to patrol the line.

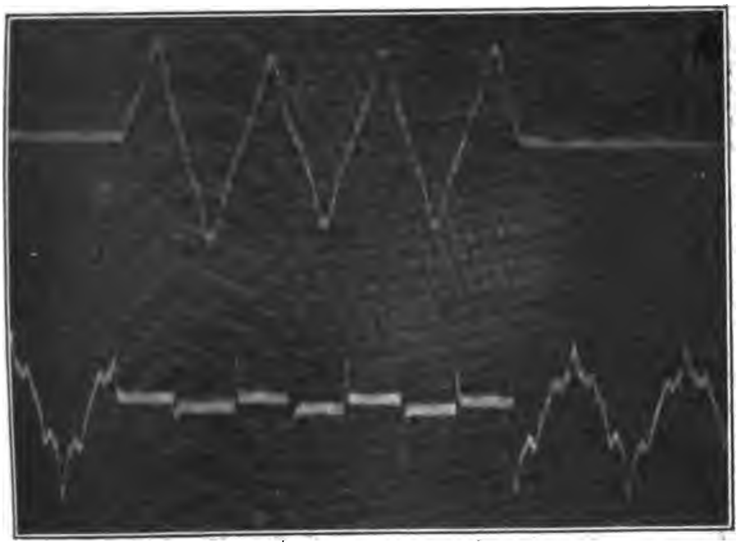


FIG. 15.—Form-V lightning-arrester current and potential waves. Non-arcing metal cylinders. 15 air gaps. Instantaneous current 115, 115, 135 amperes.

LINE TO LINE DISCHARGES.

The idea that there was a high pressure created during storms between the wires of a line, as well as between line and ground, was first advanced about three years ago. Since that time additional proof has been secured regarding this effect. A large number of telltale papers have shown that the pressure between lines has been equalized through the arresters without any discharge going to ground. In addition to this proof, several hundred spark gaps adjusted for 9 000 volt breakdown, have been placed on 2 200 volt systems, with the expectation that such spark gaps would break down only infrequently. Much to our surprise reports were received to the effect that all of the spark gaps had discharged during storms, showing the high voltage between line and line. The gaps have since been adjusted for 20 000 volts breakdown and reports of operation are now awaited.

Fig. 16.—Form-V lightning-arrester current and potential waves. Standard brass cylinders. 15 air gaps. Current and potential waves. Instantaneous current 120 amperes.

From the above it is evident that the arresters should be designed so as to limit the voltage that may be created between line and line, as this voltage may be just as destructive to the insulation as the high voltage that is created between line and ground. In the examination of telltale papers, it has been noted that discharges of greater severity, as indicated by large holes in the papers, have almost invariably occurred when the line had discharged to ground, whereas the line to line discharges have been of very much less severity.

USE OF THE OSCILLOGRAPH.

It is well known that switching and short circuits cause high voltage effects. It is, therefore, evident that the operation of the arrester itself at the time dynamic current passes over the gaps should not set up high voltage effects. If the current is broken on the zero point of the wave as in an oil switch, no oscillation will take place. The multigap lightning arrester as shown by the oscillograph records permits the current to extinguish itself on the zero point of the wave. The

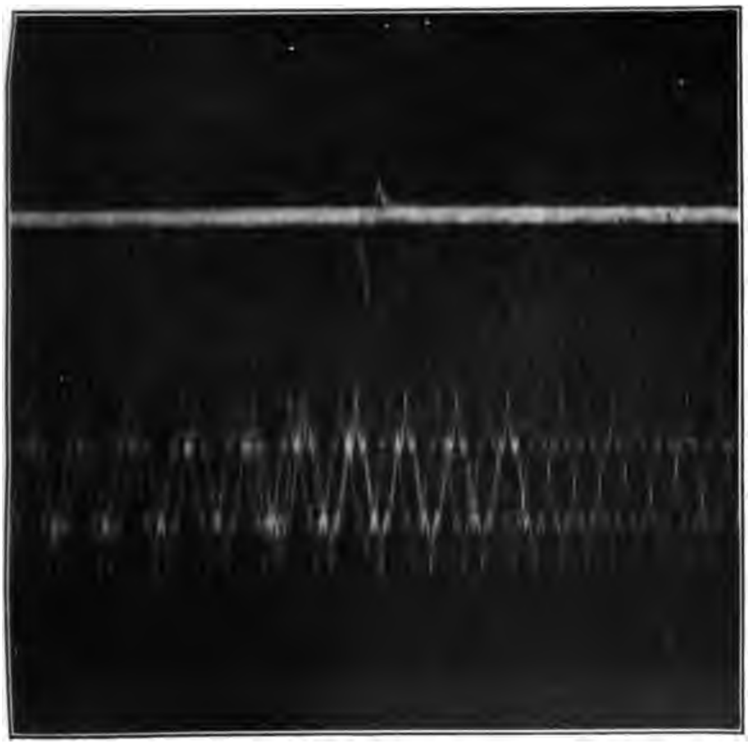


FIG. 17.—Current and potential waves. Type-U lightning arrester. Instantaneous current 17.22 amperes.

records also indicate the amount of dynamic current that has passed. With 15 air gaps the current had a value of 135 amperes as shown on record, Fig. 15, and 120 amperes, Fig. 16, whereas with 9 air gaps, 6 of them shunted by resistance, the current value did not exceed 18 amperes. Fig. 17, and in another test. 1.64 amperes, Fig. 18. The amount of current that passes over the gaps is dependent upon the point on the potential wave at which the flow of current begins, that is, whether on the peak or near the zero point of the wave.

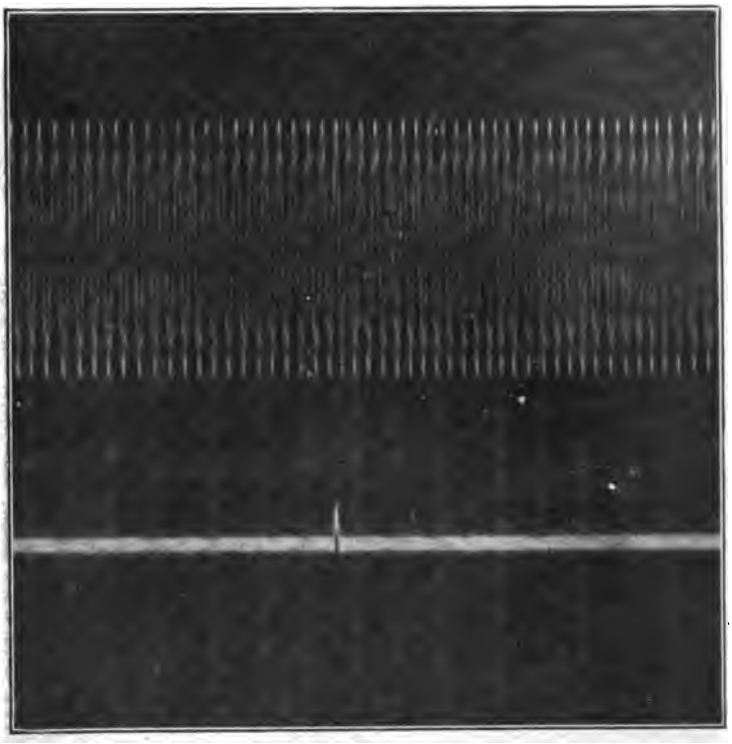


FIG. 18.—Current and potential waves of type-U lightning arrester consisting of 9 gaps, 6 of these shunted with a resistance of 250 ohms. Instantaneous current 1.64 amperes.

Sections of armature coils which have been burned by lightning are shown in Fig. 19. The discharges occurred between two phases to frame of generator and the discharge was evidently line to line. Representative telltale papers showing

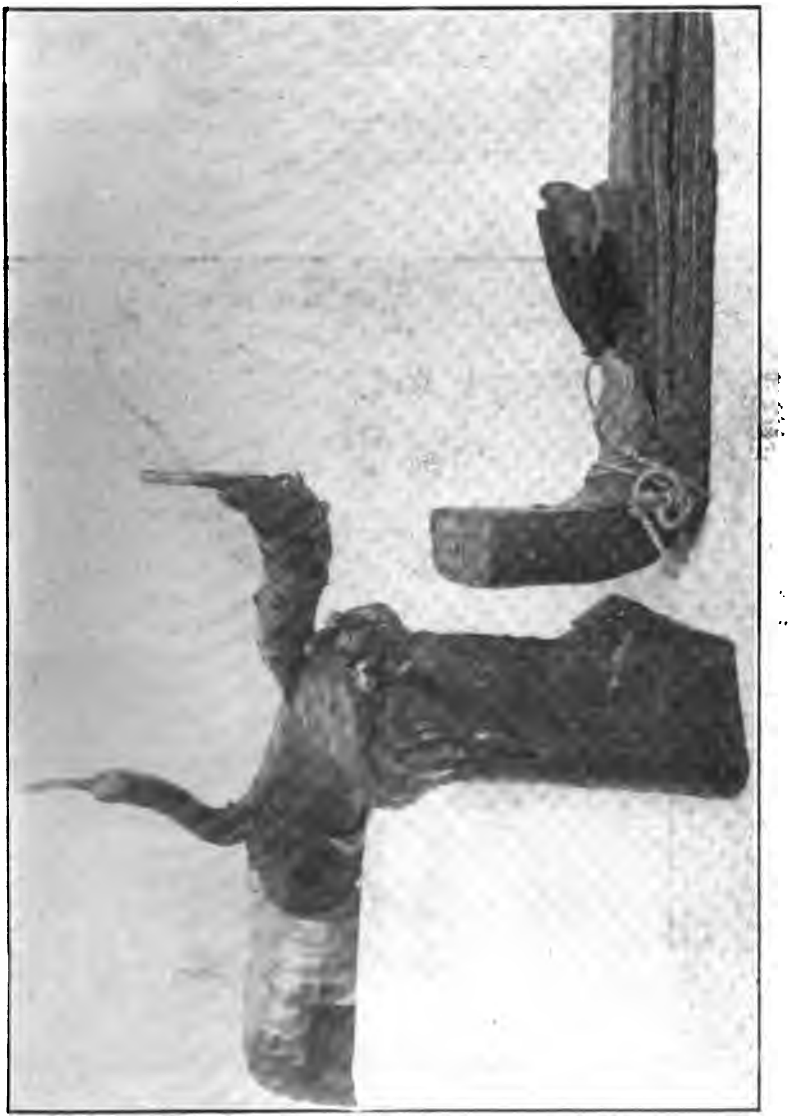


FIG. 19.

that discharges occurred over both series and shunt gaps are shown in Figs. 20 to 24. It is interesting to note that heavy discharges are those which go to ground and also that no two lines show a heavy discharge through the same arrester.

The line to line discharge is nicely shown in Fig. 21 S.B.B.

The arresters were connected multiplex and the papers have been arranged to represent the same arrangement. The single paper is the one that is placed in the units that are used between multiplex connection and ground.

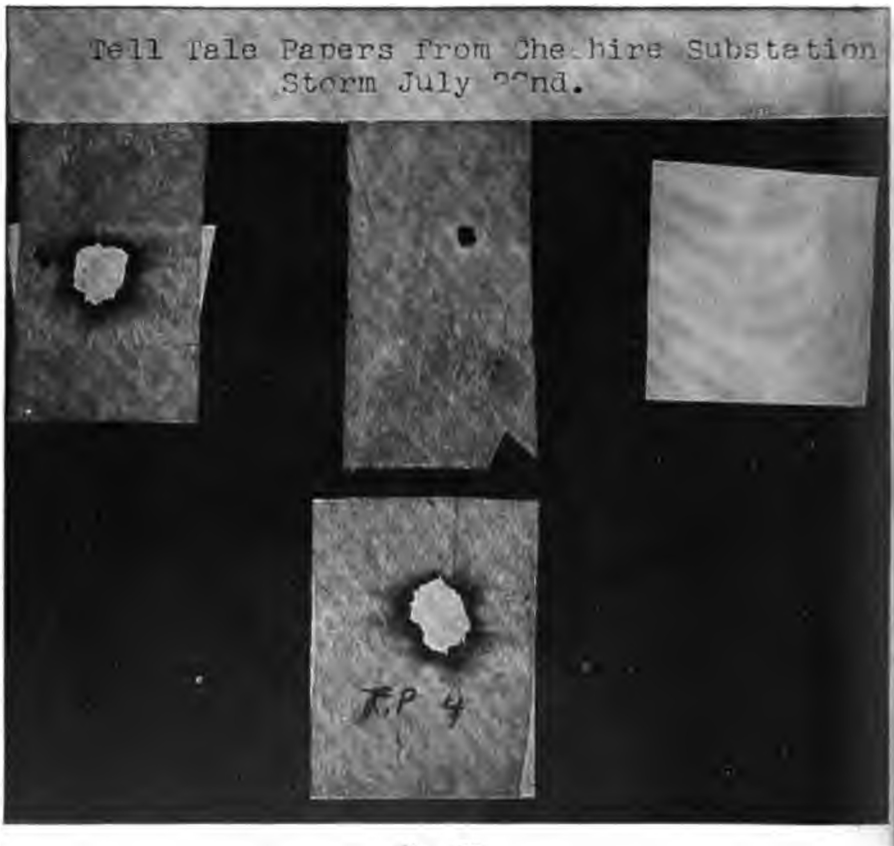
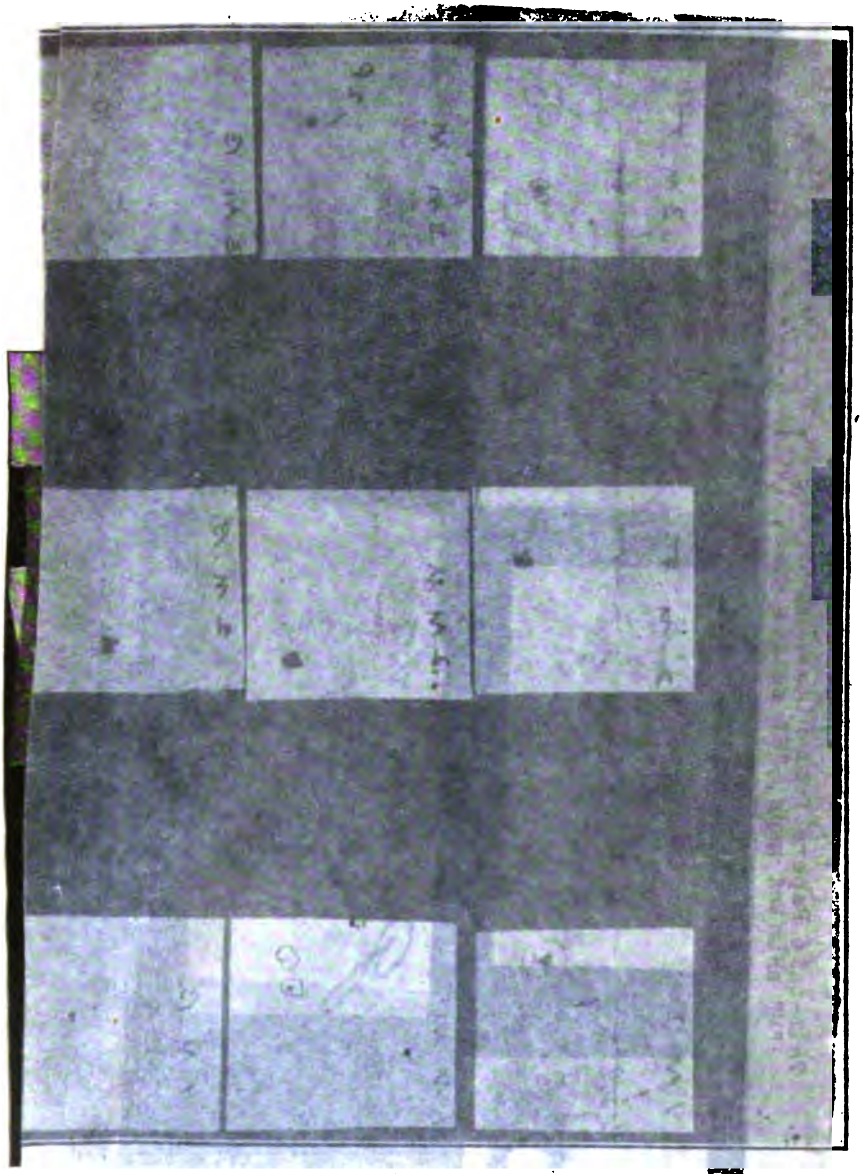


Fig. 20.



DISCUSSION ON "LIGHTNING-ARRESTERS," AT MILWAUKEE, WIS., MAY 29, 1906.

H. C. Wirt: Line to line discharges have not been admitted by some authorities, and for that reason I present additional data to that presented by me three or four years ago, in a paper before the INSTITUTE. In Fig. 21, the four papers represent the arrangement of the arresters; the lower one, the multiplex connection. You will notice the lower one is not punctured. The other punctures were made by voltage effects from line to line. As Mr. Osgood has said, the consensus of opinion expressed here to-day is that the very severe discharges are from line to ground; that wherever the record-papers show a large hole, the voltage stress was between line and ground. Whether this was part of the actual lightning stroke going into the station and then to ground, we do not know. In order to limit the dynamic effect the gaps might be increased or the character of the metal improved, and therefore a great many tests were made on non-arcing metal.

C. P. Steinmetz: Lightning, an interesting phenomenon, is of great importance to electrical engineers, an importance which is rapidly increasing with the increase of long-distance transmission. In order to judge properly of lightning protective apparatus, we have first to consider what is expected of them. If we expect that merely by putting lightning-arresters in stations and sub-stations, we will protect our system against all lightning disturbances, I think we are mistaken. No such lightning-arresters have ever been built, and I think will not be built for some time to come. What lightning-arresters can do and should do, if properly designed, is to protect stations and sub-stations against the overflow of electrostatic discharges, high voltages, coming from the line, but not to protect the system as a whole. For the latter, we shall have to go back even to the preliminary designing of the system, so as to keep high-voltage disastrous lightning phenomena out of the system as far as possible.

The construction of a transmission line is not merely the mechanical problem of erecting poles and stringing wires over them; it is also an electrical problem, and the electrical feature of the problem is not merely the selection of insulators capable of standing the transmission-line voltage. Long before that the most important part of transmission-line design must have been completed: it is to locate, topographically, the line so as to be exposed as little as possible to lightning disturbances. Before the right of way is secured, the question of lightning has to be considered and investigated, and that is not done at present to any extent. Certain precautions must be observed in designing a power house; certain precautions must also be observed in designing a transmission line. In either case the design has to be adapted to meet existing conditions. Before any work is done we should study the topography of the country, see where lightning troubles are likely to occur, and where not; see where we can pass safely through a long valley between protecting hills, and where we have to cross mountain ranges or hills at summit level, find and avoid dangerous places as far as possible; in short, use sufficient precaution and protection.

Although we are limited in this respect, as we do not know the country perfectly, we can frequently judge beforehand the most dangerous places from the topography and from a general study of the country. We know that an isolated hill or a hill crossed at summit level, is dangerous. Possibly still more dangerous is to cross a hill below the summit level on the western slope; this is liable to be a favorite place for thunder storms and lightning. In going observingly over the road we may see trees shattered by lightning; and by consulting the records existing in the country, we can frequently find out which places are more dangerous than others. If, for instance, in a transmission system the main line from the central power house immediately crosses a mountain divide near the summit level on the western slope without any protection whatever, it is hardly fair to expect that such a system will ever operate perfectly satisfactorily, and be free from lightning troubles, whatever lightning-arresters may be installed. However, the usual procedure is to secure the right of way as straight as possible without reference to lightning, and then erect the line. Frequently before the wires are up the poles are shattered by lightning. As soon as the line is up and operating the lightning troubles commence. Then we install all kinds of known and unknown lightning protective apparatus in the stations, and watch alternately the lightning-arresters and the other apparatus in the station, or both at once—burn up.

What I therefore desire to draw attention to is that the most important part of lightning protection must be done before the pole-line is erected, before the right of way is secured, in locating the line as safely as possible.

Furthermore, in the construction of the transmission line my opinion is, and I have stated so before—and recent experience more and more confirms me in that opinion—that the safest protection is a grounded overhead wire, covering the transmission line throughout its entire length. But such a grounded overhead wire must be above the transmission wire sufficiently high to protect it and must be of good conductivity, high current capacity, and frequently grounded. It is not so necessary to have a perfect ground; even less perfect grounds are satisfactory if they are frequent. Infrequent grounding, no matter how good, is not quite satisfactory. A grounded overhead wire does not mean the stringing up of a light telegraph wire anywhere along the transmission line, or the use of barbed fencing wire of the poorest kind of steel, as used by farmers. If you string such wire up and have it break continually, and wrap itself lovingly around the transmission wire, you will get more trouble than protection—and deserve it. A very satisfactory way is to have a galvanized steel cable strung from pole-top to pole-top at a tension greater than that of the transmission line. This cable at the same time serves to brace the transmission line, gives a mechanical protection and strengthening of the poles, so that further bracing is necessary only at corners. Superior to one grounded overhead wire are three wires, one above the center of the line and the others at the two sides of the top cross-arm, slightly above the level of the transmission wires. At dangerous places, such as crossing a divide, it pays to install three wires.

An objection frequently raised against the overhead grounded wire is that the transmission wire can not be put on the top of the pole, and that therefore, for a given distance of the transmission wires above ground, a longer and more expensive pole must be used. I believe that it pays to put money into the lightning protection of the transmission line. There is no excuse for using as short a transmission pole as possible, stringing the transmission line on the top of a pole, and then complaining about lightning, and finding fault with lightning-arresters, after you have economized at the worst possible and most inexcusable place.

Where dangerous locations requiring special lightning protection are encountered, one arrangement which has met with success, and which is advisable, is to parallel the transmission line by local lines, short-circuited secondary lines; for instance, where the transmission line crosses a hill. Such hills are usually covered with trees. A good practice, then, is to string parallel to the transmission line and as near as possible to it a few thousand feet of telegraph wire, merely laying it across the tree-tops and allowing it to hang to the ground. Such a wire lying parallel to the transmission line and sagging to the ground affords a good lightning protection, as shown by the frequency of its being struck All these features require consideration. The lightning protection of a system is an important engineering problem which should be considered before the location of the transmission line.

Assuming that the transmission line is located at the relatively safest place regarding lightning, assuming also that it is protected with grounded overhead wire of good conductivity and frequently grounded; assuming also that at especially dangerous places additional protection is secured—then the problem of keeping out from the station whatever electrostatic discharges may still occur is greatly simplified. Then almost perfect protection can be accorded the station apparatus. No system of grounded overhead wires will keep atmospheric discharges entirely out of the transmission line. If a pole is struck by a primary stroke, then even if the discharge is carried to the ground through a grounded wire no doubt some electrostatic charge will enter the main transmission line. If a lightning flash passes parallel to the transmission line, there will be a secondary current induced in the grounded overhead wire, as well as in the transmission line; that is, a sudden impulse, a wave of very steep front, passes along the line toward the station. But even then the grounded overhead wire, if of high conductivity, offers a protection against any such impulse passing along the wire. The grounded overhead wire is a short-circuited secondary to the discharge as primary, and so very rapidly dissipates its energy. With a perfectly insulated transmission system any impulse of high voltage would enter the station relatively little diminished; but with grounded wire of good conductivity the impulse will rapidly dampen out. The maximum decreases, and the steep wave flattens out so that when it enters the station it enters as a single impulse of moderate steepness, and can be taken care of by protective apparatus.

In locating the transmission line, no system of overhead wires can entirely keep electrostatic impulses from the line. It means that the impulses must be taken care of, and this can be done by a system of lightning-arresters in the station and sub-station.

What I desire especially to draw your attention to is Mr. Creighton's paper giving the report of an enormous amount of extremely interesting and valuable work on the subject of high frequency, high-voltage phenomena, with special reference to lightning protection, done by him under the joint auspices of the Union College and the General Electric Company. This work is not yet completed. Some of the important features shown are the time-element of the discharge; that the striking distance is a function of the time. This applies, however, only where frequencies of millions or billions of cycles are considered; that is, local high-frequency oscillations. Then a spark-gap, to break down and exert a protective influence, may require a voltage very much higher than the normal disruptive voltage of the spark-gap; in other words, a wave of very steep wave-form will not jump across the spark-gap, where a wave of flat wave-form of lower voltage will jump across; and a voltage suddenly applied will rise to values much higher than those which with a slowly-applied voltage would be sufficient to jump across the spark-gap.

A further interesting feature shown in Mr. Creighton's paper is the time-element of destruction. The usual insulating materials will stand puncture by voltages far beyond their disruptive strength, if the voltage is applied only a short time; but frequent puncture of this character ultimately leads to destruction. This is a rather serious problem when considering underground cables, as affected by switching and other methods of operation. We may imagine that the cable is perfectly safe, because it shows no puncture, no short-circuit results, while it may be punctured frequently and be weakened by it. A single puncture, if due to a high-frequency oscillation; that is, a high electromotive force applied for a very short time, will not be followed by a short circuit or destruction, but a succession of such punctures will ultimately destroy the insulation.

One curious feature described in the papers in connection with the multigap arresters is the apparently enormous striking distances reached by moderate voltages. In the 33,000-volt arrester, over 600 gaps of $\frac{1}{32}$ in. each are used in series. $\frac{1}{32}$ in. between spheres, depending on the character of the sphere, requires somewhere between 1,000 and 3,000 volts. Assuming 1,500 volts per gap, 600 gaps would require 900,000 volts, and yet 60,000 volts at high frequency will jump across the whole system of 600 gaps. Here is a system of spark-gaps which is selective for the frequency; that is, which requires at very high frequency a very much lower voltage to discharge than at low frequency. It is discriminating, somewhat similar to the condenser. A condenser also takes a larger current at higher frequency, but the difference between the condenser taking care of the high-frequency discharges and the multigap is that beyond the voltage limit the condenser punctures and may be destroyed, and the multigap jumps across, discharges, and then recuperates again, provided the dynamic current which follows the discharge does not hold long enough to result in a conflagration. To avoid the latter requires the use of a large enough number of gaps in series.

This selective feature or discriminating action is very interesting, and has a bearing far beyond the mere lightning-arrester, because I believe it is the same phenomenon by which a lightning flash may pass through distances of miles without requiring a voltage anywhere near what you would expect from the striking-distance curve, extended to distances of some miles. If we say it requires 10,000 volts per inch, then a lightning flash of one mile in length should require about 600 million volts. It is not probable that this is the case, and I believe the phenomenon of the lightning flashes is of the same character as that observed on the multigap arrester: a successive series of discharges, from point to point, from electrostatically charged rain-particle to rain-particle, the capacity of the successive particles producing a very high-frequency oscillation, and so resulting in a successive breakdown.

The selective action of the multigap lightning-arrester, regarding frequency, may be illustrated by the diagrams Fig. 1 to 3. Assuming a series of gaps, on one side connected with the ground G, or potential zero, on the other side connected to the line L; that is, to a point which is at an alternating voltage. At a very low frequency or a steady applied voltage, the potential distribution from line L to ground G across the arrester would be a straight line, 1 of Fig. 3.

If then E = impressed voltage between line L and ground G, n = number of gaps in series, the voltage per gap is $\frac{E}{n}$, and if $\frac{E}{n}$ is greater than the voltage required to break down a gap, or the disruptive voltage per gap, the arrester discharges. Or inversely, if e = disruptive voltage per gap, $E = n\,e$ is the minimum voltage at which the arrester discharges. Or, with 1,500 volts per gap, in a 33,000-volt circuit, 33 gaps in series gives a discharge voltage of 33×1,500 = 49,500 volts, or 50% above line voltage, at low frequency or steady stress; that is, under

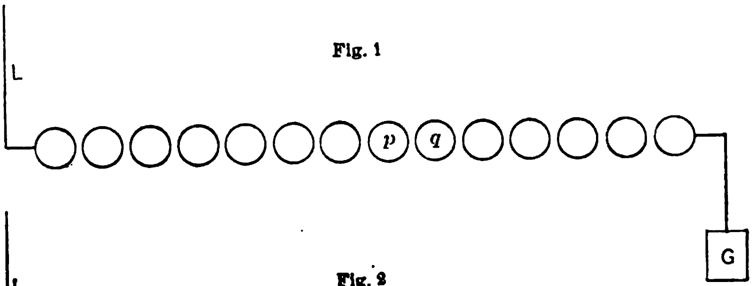


Fig. 1

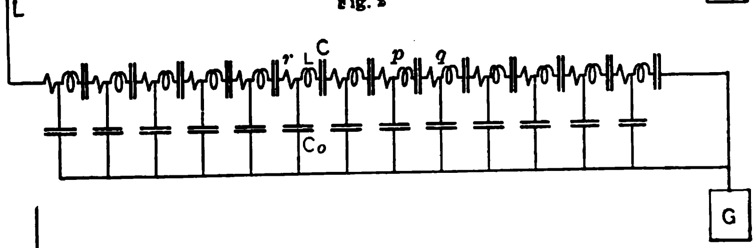


Fig. 2

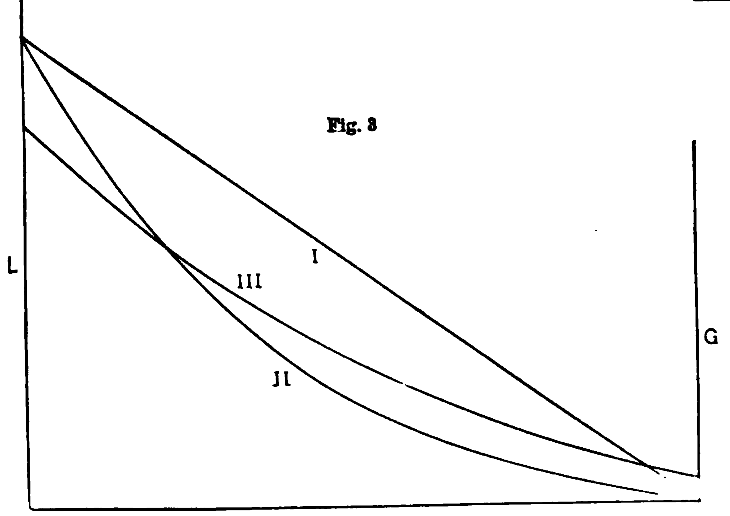


Fig. 3

conditions where the capacity of the arrester cylinders is negligible.

Entirely different, however, are the conditions at very high frequency, where the effect of the capacity of the arrester cylinders is noticeable. The cylinders of the multigap arrester have a capacity against each other, and a capacity against ground. The arrester also has an inductance, appreciable at very high frequency, and a resistance that is appreciable even without the use of any series resistance in the arrester circuit, since at very high frequency the current does not penetrate into the metal of the cylinders, but passes only through a thin surface film, of a depth of about a thousandth of an inch at 10 million cycles.

The multigap lightning-arrester thus represents a circuit having distributed resistance, inductance, and capacity, differing from a transmission line by having distributed capacity of two kinds: series capacity, the capacity between adjacent cylinders; and shunted capacity, the capacity of the cylinders against ground, while the transmission line contains only the latter form of capacity.

Diagrammatically, the multigap arrester, Fig. 1, can be represented by a circuit as shown in Fig. 2. Each arrester cylinder absorbs a charging current, which is proportional to the frequency and to the potential difference of the cylinder against ground. If, therefore, curve I I Fig. 3, represents the distribution of potential, against ground, along the arrester, the same curve I I also represents the charging currents of the successive arrester cylinders.

The charging currents against ground, of all the cylinders from q to the ground Figs. 1, 2, must pass the gap between the adjacent cylinders p and q; that is, the charging current of the condenser represented by two adjacent cylinders p and q, therefore is the sum of all the charging currents from q to ground, or, in Fig. 3, proportional to the area, between q and G, of curve I I, and represented by curve I I I. The potential difference between adjacent cylinders p and q is proportional to the charging current between these cylinders, hence also represented by curve I I I, and the potential difference of cylinder p against ground G, or curve I I, then, is the sum of all the potential differences between adjacent cylinders, from p to G; that is, proportional to the area of curve I I I, from p to G.

This gives a curve of potential difference against ground, *II*, which is very steep near the line L, flat near the ground G. If the potential difference against ground were a straight line *I*, as at low frequency, the charging currents, against ground, of the cylinders would be proportional to their distance u from ground G, and the potential difference between adjacent cylinders (curve II), proportional to u^2; hence the potential difference against ground, or the sum of successive potential differences between cylinders, proportional to u^3; that is, strongly curved. Starting, then, with a curved line of potential distribution against ground, means that this potential distribution varies with a higher power than the cube.*

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*The curve of potential distribution is an exponential, and its derivation is given in the Appendix.

It follows herefrom that with the same impressed electromotive force E between line L and ground G, the curve of potential distribution is very much steeper at the line side, at frequencies where capacity effects are appreciable, $I\ I$, than at low frequency or steady stress, I; and the potential gradient or the potential difference between adjacent cylinders is very much higher in the former case. Inversely, the same limiting potential gradient, the breakdown voltage between adjacent cylinders at very high frequency, is reached at very much lower voltage than at low frequency. Hence a much larger number of cylinders can be used at very high frequency, and still the discharges take place freely at a voltage far lower than the voltage which at low frequency would be sufficient to discharge across a far lesser number of gaps.

At high-frequency impressed voltage, as soon as the breakdown voltage is reached at the first gap on the line side, this gap discharges and so puts line potential on the second gap; this breaks down, and thus successively the discharge passes from the line over gap after gap, either to ground or, if not sufficiently powerful, gradually tapers out, just as frequently observed on lightning flashes between clouds. At the end of the half-wave of machine electromotive force of low frequency the arcs between successive cylinders extinguish, and can not start at the next half-wave, due to the rectifying character, or undirectional conductivity, of a low-temperature metal arc. The interesting result then follows, that even with an infinite number of gaps from line to ground, the potential difference between adjacent cylinders near the line terminals is finite; and so at the definite impressed voltage, a discharge takes place into an arrester consisting of an infinite number of gaps.

It also follows, as the effect of the capacity against ground, that if a large number of cylinders are connected between two lines a and b, with the middle point of the cylinders c grounded, and the ground c then disconnected and point b grounded, the potential gradient along the cylinders is entirely changed, becomes practically zero at b, and more than twice its former value at a, and so a discharge takes place from a to b, with the ground on b, while no discharge occurs with the ground on c, although in the discharge circuit from line a over arrester to line b no apparent change takes place. This explains the flashing-over of lightning-arresters, which frequently takes place when one line grounds, without any increase of potential difference between the lines.

The multigap lightning-arrester so discriminates in favor of high frequencies, that very high-frequency oscillations discharge at a voltage far lower than the normal low-frequency line voltage, over such a large number of gaps, that even without, or with practically no series resistance, the low-frequency line voltage can not maintain an arc across the gaps, and so no need exists, by the use of high series resistance to assist the arc-rupturing power of the gaps, at a sacrifice of discharge capacity. The danger of producing an oscillation by the low-resistance discharge, seems obviated by the non-arcing character of the short metal gaps, which rupture the circuit at the zero value of current; that is, on the principle of the arc rectifier do not permit a reverse current to start.

With a very large number of gaps, of a total length several times greater than the striking distance of the low-frequency line voltage, the mere multigap offers little protection against a steady electrostatic stress or a low-frequency voltage. It is therefore necessary to shunt a very large number of gaps with a moderately high resistance, leaving unshunted only sufficient gaps to hold back the line voltage. That is, with a disruptive voltage of e per gap, and an impressed voltage E on the line, allowing 50% margin, $\frac{1.5\,E}{e}$ gaps would remain unshunted, to take care of low-frequency and steady stress, while the remaining gaps become active at high-frequency oscillations.

Naturally, even such a lightning-arrester cannot completely protect the system from low-frequency high-power surges, such, for instance, as occurred when the boy threw the umbrella into the lines. I do not think we have any certain means of protection against this sort of thing. They are oscillations of such low frequency that no reactive-coil could take care of them. With voltages infinitely high, currents of the magnitude of the short-circuit current of the system, the only possible way seems to short-circuit the system by a dead metallic short circuit. Then the oscillation will disappear; but that means a shutdown. I do not wish to be misunderstood; I do not mean to say that a short-circuiting arc on a long-distance transmission system always results in a destructive low-frequency surge; on the contrary, most short circuits are probably relatively harmless, but occasionally a short circuit by a flaring arc results in a low-frequency surge, which makes up in destructiveness for the harmlessness of many short circuits which may have preceded it.

P. H. Thomas: Perhaps the most interesting subject suggested for discussion is the question of shunt resistance in lightning-arresters, and I shall take a few minutes to tell something of some experiments I have made in connection with such apparatus, which may throw additional light on its action.

The original idea is of quite an old date. The question is how, by the use of shunt resistances, to extinguish the dynamic arc which follows through a lightning-arrester after its discharge. A study of the non-arcing power of a multigap arrester, as explained in the second paper, shows that an individual gap seems to have a certain definite power of extinguishing an arc; in other words, that an arc involving a certain amount of energy or current will be suppressed at the end of the first alternation, or at the end of two or three alternations, while, with a larger amount of energy, the arc will so heat the cylinder or otherwise affect it that the arc will continue.

In studying this phenomena, I found certain laws governing the non-arcing power. These results showed that the non-arcing power is very much reduced in circuits of large power; therefore, to insure that the worst conditions should be observed, experiments were made in a number of places, including Niagara Falls, where work was done on two of the 5000-h.p. generators parallel, showing there was ample capacity behind the circuits to give us the worst conditions we could expect to reach in practice.

The laws can be tabulated roughly as follows: if we plot as ordinates the number of gaps that are just non-arcing on a definite circuit, and as abscissæ the current through the gaps, we get a series of curves rising with increasing currents, each curve corresponding to a different inductance in the circuit (see Fig. 1). The important elements being the current and the total inductance of the circuit. The actual current which flows through an arrester in any given case depends only slightly on the characteristics of the arrester, but mainly on rest of the circuit; that is, the power of the generator, ground resistance, the impedance in the line, and field reaction, etc.

I think the most feasible way to get at the non-arcing power of a given arrester is to calculate the short-circuit current in the system to which it is connected, and determine the total inductance. We can then determine the non-arcing power of the arrester from the curves alone. I do not remember the exact values, but an increase in the inductance in the circuit greatly decreases the non-arcing power of an arrester, so that it may sometimes be more difficult to extinguish a highly inductive arc of small current strength than a non-inductive arc of much greater volume. Fortunately, in actual installations there is comparatively little inductance in circuit, but with small generators, especially old-fashioned generators with polar armature, or in cases where the short-circuit occurs through a long line, that inductance may be an important factor. So much for the non-arcing power of the gaps.

The increasing of non-arcing power by the use of shunt resistance is now easily controlled. When a resistance shunts a number of gaps, the arc will leave the gaps for the resistance, provided the ohms per gap are of the proper value. What determines the critical ohms per gap is the current strength in the gaps which are shunted. The relation of current in gaps to critical ohms per gap can be well shown in a curve. The curve is shown in Fig. 2. It is evident from the curve that on small currents the shunt resistance is very effective, but with large currents in the gaps the shunt resistance has little value.

In designing an arrester to meet all conditions, using shunt resistance, we must so proportion the arrester that the current on short circuit, that is, on the discharge of the arrester, will not exceed a certain amount, which amount will allow of effective use of shunt resistance. We find on large systems that this amount is greatly exceeded if there is no limiting series resistance. That is, on a circuit like that at Niagara Falls, the shunt resistance would be of comparatively no value if we allowed a complete short circuit on the system through the arrester.

The introduction of the series resistance gives a definite limited short circuit current, and taking into account the greatest possible inductance in circuit and the number of gaps necessary to hold the normal voltage, a suitable number of series gaps can be chosen, which will be able in all the cases assumed to suppress the arc. Now the current in the gap being known, it is possible to determine the maximum number of ohms per gap that can be used to withdraw current from a portion of the gaps called shunted gaps. Then a suitable number of shunt resistances can be connected around an appropriate portion of the series gaps, thus converting this part (which may sometimes be the whole) into shunted gaps. By this method the maximum effectiveness of shunt resistance may be obtained. This matter was discussed in a paper at the Great Barrington meeting of the INSTITUTE in 1902.

Mr. Osgood's paper is very much worth while. He has carefully and frankly given us the facts, and added materially to the definite knowledge of the way things happen.. If other engineers having similar information will do the same thing, it will not be long before we shall be able correctly to determine the effectiveness of different types of arresters. The important inference to draw is just what do the results so far show. There are two points to consider; the non-arcing power of the arresters, and their protective power. Mr. Osgood states the non-arcing power of his arresters is not satisfactory yet. He expects this year, with the shunt resistance, that they will be, and we shall all look with a great deal of interest to learn the result of this season's lightning.

Mr. Osgood finds a great gain in protection obtained by the elimination of the original series resistance, but it should be noted that the series resistance which was eliminated was of a very high ohmic value, each rod having 250 ohms, and some 32 rods, giving 8000 ohms, in the ground connection. Although the elimination of this resistance may have been found distinctly beneficial, it does not prove that a much lower series resistance, such as will be chosen by the method of design described above, will have a harmful effect.

The second paper is a very admirable exposition of some of the precautions that you have to take in experimenting in a laboratory in connection with the lightning arrester study. There is nothing so easy as to be misled and mistaken in this sort of work, so as Mr. Wirt says, it is important to check up very carefully from the outside investigation. I believe, however, that laboratory work is important. But we must use a great deal of common sense and care in inferring what results will be produced on a transmission line where we have what are numerically very different conditions. For instance, we never have the small manifestations which give extremely high frequency discharges. You cannot, with any considerable amount of energy—enough energy to do any harm—get an oscillations as rapid as a billion per second. I think it would be safe to rule out from our tests, as to final judgment on arresters, any of the extremely high-frequency tests.

I would like to ask Mr. Creighton how the time period of 200 microseconds given as the time necessary for ionization to become effective was measured or determined?

E. E. F. Creighton: Curve 3-*B* represents the discharge of the condenser through the resistance. The static machine voltage was 150 kilovolts. Now, from the static machine gap *G* short circuits, we may assume that the 150 kilovolts appears at the terminals of the larger resistance and also at the terminals of the needle gap *Q*. If *Q* is set on 150 kilovolts it will not spark. It is necessary to set *Q* on as low as 65 kilovolts before it begins to spark. I have assumed that the time taken for the voltage to drop from 150 kilovolts to 65 kilovolts on the discharge curve 3-*B*, is the time necessary to ionize the gap *Q* and make it conductive.

P. H. Thomas: Have you made any careful study theoretically to find out whether these apparent voltage differences are not due to the different methods of generating or measuring voltage rather than to a true time lag in ionization? The evidence is not very clear, is it?

E. E. F. Creighton: The evidence is very great in favor of this, in that we have been able to observe it in some ways that I cannot describe at the present time.

P. H. Thomas: Mr. Wirt says that the pulling off of the ground connection on the three-phase line caused the rise of potential. Was it the pulling off of the ground, the throwing on of the ground, or was it a continuous rise?

H. C. Wirt: It was the pulling off, starting an arc over the line.

P. H. Thomas: I would like to suggest an explanation for that action, which I have suggested before, and which is really of considerable importance, if it is the true one. Suppose we have a transmission line, step-up transformers, and a generator. In disconnecting the line when unloaded by opening the switch we shall usually leave the line charged to maximum potential, since the charging current will open at its *o* point when the voltage is a maximum. Consequently at the end of one alternation we have double the potential to ground impressed between the two switch-jaws which are in the process of opening. Therefore we may get a recharging of the line, but at double potential, which will cause violent oscillation and a certain rise of potential at reflecting point sufficient to cause arresters to discharge. This result may occur a number of times in pulling off and charging current. Those who have handled high-tension lines know the sound you get from such an arc, a sharp cracking, indicating that there is a serious static discharge.

H. C. Wirt: The same effect has occurred without any line at all, just at the transformer itself.

P. H. Thomas: You have capacity in the transformer?

H. C. Wirt: Yes.

P. H. Thomas: Here is a possible explanation of the blowing of primary fuses in lightning storms, with no apparent damage to the apparatus. As a result of the local concentration of potential near the terminals of a transformer, lightning may cause a spark between neighboring parts, which starts a flow of current cut out by the blowing of the fuse. The injury would often be so slight as to be readily repaired by the insulating oil of the transformer.

E. E. F. Creighton: The first requisite in laboratory tests is to have sufficient power to puncture the insulation. With three million cycles per second (calculated), we have punctured five thicknesses of 0.1-in. press-board, jumped 12 in. across a needle-gap, and jumped 18 in. on the surface around the insulation. It seems to me that this is sufficient to prove there is a charge that can damage the insulation. I think we sometimes get a frequency of three million on the line.

Dr. Steinmetz has shown mathematically that the natural frequency of a line may be as low as a few hundred cycles, but the line may oscillate electrically in segments. Furthermore, there are local circuits of low inductance and capacity. Oliver J. Lodge has estimated the frequency of certain lightning strokes at one million per second. It seems to me if such a stroke took place near the station this frequency would be transmitted directly to the apparatus; if, on the other hand, it took place far out on the line, the high frequency would be superposed on the lower frequency of the line surge. When the frequency approaches a billion per second, such as found in the multigap arrester, then the quantity of electricity involved seems to be too small to damage insulation when the time of application is short.

P. H. Thomas: Mr. Creighton apparently infers from the amplification of the harmonics of the current wave to the condensers, as shown in Fig. *P* and that a corresponding voltage increase must follow. This conclusion is erroneous, for this current is determined by the wave-form of the generator and the capacity of the condenser. If the current resulted from a condition of resonance, there would evidently be a correspondingly high potential; but as in this case the current is determined primarily by the generator voltage and the capacity without regard to the value of any inductance that may happen to be included in the circuit, there will be no corresponding rise of potential.

J. B. Taylor: Mr. Creighton states fairly well the position of the man who attempts to build a successful lightning-arrester: he is between the devil and the deep sea. It is commonly said that " lightning never strikes twice in the same place," and the saying shows the difficulty of getting accurate data as to which type of arrester is better than another. Mr. Osgood's experience might lead him to dispute the old saying, as 56 interruptions in one season show that lightning does strike twice in the same place.

The proverb should be, " lightning never strikes twice in exactly the same manner." Consequently, it is not right to take data from one circuit in one part of the country, operating at a certain frequency, with a certain voltage, a certain type of transformer and a certain type of arrester, and conclude that this arrester is better than another type of arrester, because fewer transformers broke down than on a system with the other type of arrester, in another part of the country, operating at a different frequency, different voltage, with different transformers—with perhaps all the essential features varying.

The laboratory tests, of course, show the direction in which to look for data in the outside work. While such tests alone are not likely to produce a successful arrester they should not be discouraged. The best plan is to establish a laboratory in a sub-station of a transmission system in regular operation.

Mr. Thomas takes issue with Mr. Creighton on his point that the irregular current wave shown in oscillogram, Fig. P, is evidence of increased e.m.f. due to grounding one terminal. I agree with Mr. Thomas that this is virtually nothing more than wave of current in a condenser, the e.m.f. wave, as is almost always the case, departing from a perfect sine wave. It is almost impossible to get any wave of potential which, impressed on a condenser, will not show all kinds of ripples in the current wave.

Fig. 1 shows a fairly smooth wave, and yet put it on a condenser and there is no telling what the current wave will be. For example, at the point *a* on the e.m.f. wave there may be an irregularity too small to be noticeable, but yet sufficiently steep to cause a large rush of current as shown at *a'* on the current wave. In other words, the flow of the current in the condenser is entirely dependent on the *rate of change* of e.m.f. at its terminals. The arcing ground, however, is quite another matter, as here a number of secondary actions come into play. In effect we have a wireless telegraph transmitter sending along waves of abnormally high frequency, which in turn may give abnormal difference of potential in parts of the circuit.

For the same reason I think the data quoted to show that in many cases there is a high potential between line and line are open to question. If this potential were in all cases measured by a simple spark-gap, it might be fair evidence. Most of the evidence to show that there is high potential between line and line is a discharge over a complicated system of condensers; namely, the cylinders of a lightning-arrester.

The evidence to show that there is abnormal potential between line and line is, that under some circumstances, the arc held across this path, without arcing to ground. Dr. Steinmetz has illustrated the complicated system of condensers, and at abnormally high frequency these condensers are charged in succession. This charging of cylinders may occur on two phases of the arrester; that is, the gaps may be broken down on two lines to the cross connection, or enough may be broken so that the normal line potential is able to break down what is left. Consequently, we get a discharge from line to line. To my mind we have better evidence of abnormal frequency than abnormal potential.

A remaining point I wish to make is the matter of measuring potential by means of a needle-gap. Mr. Creighton shows curves which indicate that quite different results are obtained in cases where one side of the system is grounded, and this should always be borne carefully in mind in making high-potential tests in which the needle-gap is used to determine potential value. The distribution of potential over the system is different when one side is grounded, or the middle is grounded, or no point at all is grounded. (In the last case what should be the neutral point may be far from ground potential). Failure to determine a definite point of the test system at earth potential is responsible for much of the discrepancy in spark-gap curves given by different observers. Of course the wave form comes in, and many other things, but often no attention is paid to earth potential, although conductors and non-conductors at this potential, are on all sides—walls, floor, ceiling, tables, the observer, and even the air itself.

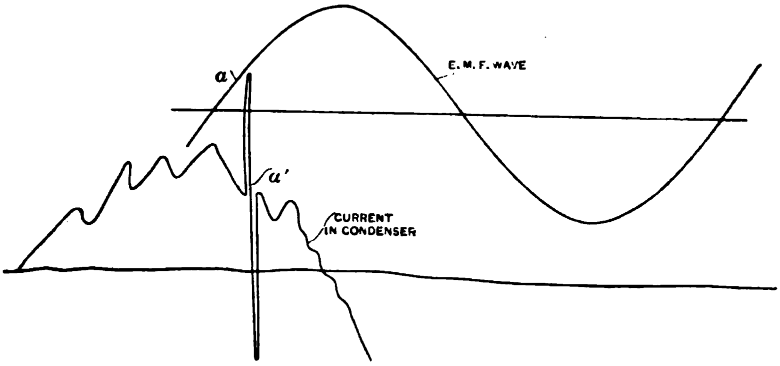

FIG. 1.

The breaking down point of an air-gap is largely affected by the distribution of potential in and near the gap. Consequently proximity of bodies at earth potential will cause one distribution if one of the needle-points is grounded and another distribution if the ground is somewhere else. With needle-points in air a given e m.f. between needles will break down a longer gap if one side of the system is grounded. This is doubtless due to the longer brush discharge from the opposite needle under these conditions, the brush being probably a forerunner of the complete breakdown.

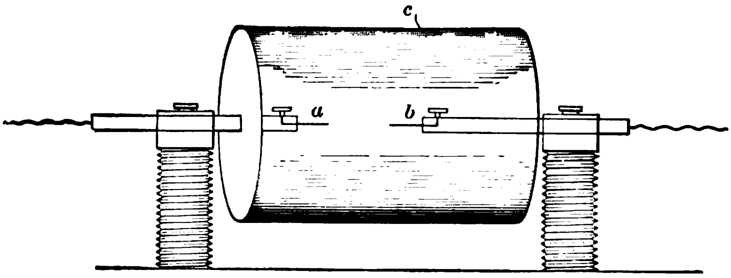

FIG. 2.

Fig. 2 shows a shielded spark-gap. A metal cylinder or screen surrounds the needle points, and this screen is connected to one of the needles. With such a piece of apparatus, any part of the system may be at earth potential, and yet have little effect on the distribution of potential around the points so that the conditions will be fairly constant. The use of such a device will eliminate some of the discrepancies and unexplained points in connection with high-potential measurements by means of needle-point spark-gap.

N. J. Neall: As some of the gentlemen present will recall, in a paper which I presented at a meeting of the INSTITUTE last fall I described the operation of tell-tale papers. To-day we have further evidence along the same line. We have, moreover, evidence that a laboratory test is feasible, although it is not conclusive; and I think this fact must be borne in mind, that if you are testing any device for relative freedom of discharge, or what not, all the devices must be subjected to the same test, under the same conditions, and at the same time. It is not fair to say that A's apparatus here is the same as B's apparatus there, unless they are subjected to the same test.

The real criterion of the best practice to-day depends on two characteristics; large current, and large voltage. Another condition which is of the greatest importance to transmission to-day, is protective apparatus suitable for 50,000 volts and higher. Designers are not disturbed by a 25,000-volt or a 6,600-volt proposition. It is in the 50,000-volt plant that you find people hunting for new devices to take care of these disturbances, which the standard protective apparatus does not seem capable of taking care of. I do not believe that these tests developed under the auspices of the Westinghouse Elec. & Mfg. Co. or the General Electric Company are suitable for demonstrating the applicability of 50,000-volt apparatus.

Such a requirement on lightning-arresters or other protective apparatus in the laboratory is just as difficult as the point which Dr. Steinmetz brought out yesterday of heat tests of large capacity alternators. In the latter case it is absolutely essential; in the other case there are other ways of going about it which I think are entirely feasible. The one method which should be developed more and more is the testing in practice, and segregating if possible, such elements of disturbance external from those which are inherent in the system, as may be done, and distinguishing how far protective apparatus is capable of taking care of the real disturbances it is put up to meet. So I think that if it were possible to have a large line with protective apparatus installed on it, and equip it with tell-tale papers and spark-gaps, and have the test extend over a long time, that we would have in practice a pretty close approximation after four or five years as to what the particular apparatus is good for.

This leads me to speak of another point which has been under discussion. You all know that the horn type of arrester has a great many admirers who, unfortunately, have not yet demonstrated conclusively that it is suitable for what it is intended. It has also been stated by Dr. Gustav Benischke of Germany that in tests which he has made (and he has also quoted tests by Slaby), comparing the action of the horn lightning-arrester with that of the multigap lightning-arresters that the multigap might give rise, by reason of resonance, to worse conditions than those that caused them to operate originally, while the horn gap does not. I would ask Mr. Creighton if in his tests he has made any oscillograph determinations to show this fact, or whether he has been able to disprove the statement of Dr. Benischke.

A point was brought out by Dr. Steinmetz this morning, which I think is one worthy of notice, and that is a new test which may be suitable for cable insulation tests—it is not an uncommon thing for cables to break down, which in the laboratory have stood the normal tests, even double potential, and in so far as my remembrance of such occurrences goes, the majority take place at the time of a short circuit (and yet these short circuits are apparently not of such tremendous quantities that they would destroy the apparatus if the line had been of standard overhead construction throughout), or with switching, but less so, which show that they are simultaneous with what is presumably high-frequency phenomena. Therefore I think that it would not be an unreasonable demand on cable manufacturers to require of them an equivalent gap test of the cable (or by sample) which they are providing, and give it just as much importance as the double-potential test.

P. M. Lincoln: It seems to me that the things which the lightning-arrester is expected to do can, with a fair degree of accuracy, be divided into three distinct functions. First, there is an endeavor to provide apparatus which will prevent the high-potential discharge which gets on the line in some manner from getting into the apparatus. This is done by placing a choke-coil between the line and apparatus to be protected. It is almost universally admitted that the choke-coil as at present used is a successful piece of apparatus for doing this. I believe that theory and practice alike unite in pointing to this fact, that the choke-coil does prevent to a very large degree these high potential discharge waves from getting into the apparatus, both by suppressing them, flattening them out, and reducing the abruptness of the wave front. The second thing the lightning-arrester engineer is trying to do is to provide a path by which the high-potential discharge can escape. The air-gap which is universally used for this purpose is an entirely successful device. It is merely the provision in the line of a place of considerably lower insulation than the normal insulation, so that the high potential coming to that point will discharge at that point. The third thing he is trying to do is to provide apparatus to prevent the dynamo current from flowing over these gaps. That is the most difficult thing he has to do in high-tension apparatus. I believe that the engineer who attacks that problem, and solves it, undoubtedly has a successful lightning-arrester. That is the point on which the energies of the engineer should be concentrated.

Charles F. Scott: I wish to emphasize the value of papers of this character to the INSTITUTE, and also to refer to the relation between the subject-matter presented in the papers to-day and that which has appeared formerly. Nearly all of the papers and discussion of the last few hours have been based on non-arcing metal. To those who are younger among us, who are not familiar with the history of non-arcing metal, I would say that the discovery and the original work in connection with non-arcing metal was done by Mr. A. J. Wurts. His own account of his work will be found in early INSTITUTE papers, and any one interested in the subject should refer back to these papers. It is quite interesting now, after these new investigations to note that the best result shows only some five per cent. or ten per cent. improvement in the character of the metal. Another point Mr. Wurts foresaw and discussed was the effect of resistance in the discharge circuit. A year or two after Mr. Wurts' first work on the problem, Mr. Henry Noel Potter began investigations in regard to non-arcing metal, and did some important laboratory work. He placed an inductance in series with several gaps and sought to measure the voltage across one gap during the time the current was flowing. He measured across one of the gaps, and immediately the whole current disappeared; that is, the voltmeter was a shunt resistance across a portion of the gaps. That arrangement corresponds to the type of arrester which we are discussing to-day. This principle was employed in the early types of switches at Niagara Falls. Later types of switches have come in to displace this early form, but the non-arcing metal gaps with shunt resistance solved the very difficult problem presented a dozen years ago of developing a switch to handle 2,400 volts at 1,000 amperes.

The non-arcing arresters without resistance held their own for many years, but finally there were reports of their inadequacy; they were short-circuited and did not interrupt the current. It was found that cases of this kind were apt to be coincident with larger generators, generators of good regulating features, which would allow a very large current to flow to the arrester. It was thought best to have recourse to Mr. Potter's plan of putting a shunt around some of the gaps. Mr. Thomas was working on this problem, and I remember some years ago I asked him to determine the resistance necessary for the shunt, so that it could be applied. I expected a report on the second or third day, but he was very slow in making his report, and after three or four months he gave me a part report, and for a year or so he was working on the problem to secure more data. When he sought to determine the proper shunt resistance he found that the problem was not a simple one, and that there was a necessity for series resistances. This lead to the whole line of work which he has indicated to-day

Speaking of the practical service of lightning-arresters, the low-equivalent arrester, which is the outcome of Mr. Thomas' work, has been a commercial article for a number of years. I took occasion to make inquiry a few days ago of our engineering department as to the general success of this apparatus. Hundreds have been installed, and I find that the number of complaints, due either to damage to arrester itself or to inefficient protection, are comparatively few, of the order of one to three per cent.; there was some defect here and some little trouble there, but on the whole there has been a very satisfactory result.

Mr. Steinmetz says that the first thing to do is to lay out a proper route for a line; that is excellent and sounds well in the meeting here, but under actual conditions that advice will often fall short. I recall one line with which I am more or less familiar; it runs across a mountain range and then crosses a valley some eight or ten miles in width. The troubles come in the valley, because in crossing the mountains the line does not go across the highest peaks, but through passes, so that the line there is well protected by the higher peaks; but in the valley through which the storms sweep it is out of the question to avoid the effects of lightning, and it would require a detour of a hundred miles to avoid the valley.

Mr. Steinmetz has shown that a series of non-arcing metal cylinders arranged in line so as to give a large number of gaps between the circuit and the earth is really a complex form of condenser in which there is capacity between adjacent cylinders and between each cylinder and the earth. From this elementary form it is seen that the static stress across the gaps near the circuit is greater than that across the gaps near the earth. In practice the relations are often not of so simple a character. The cylinders and gaps are not placed in a straight line and the arresters between the several wires and the earth are often not far removed from one another. There is, therefore, a capacity effect from certain cylinders of an arrester to various other cylinders in the same arrester, as well as to the arresters and other parts connected with the other wires of the circuit. The tendency to discharge between cylinders, particularly those near the line, is therefore affected by the disposition of the other parts of that arrester and of the other arresters, so that the critical voltage for breakdown across an arrester is a function not only of the number of gaps but also of their position with respect to other parts of the circuit. This is, I believe, the explanation of some rather puzzling situations. In one case the number of arrester gaps required at one point on a circuit was many per cent. greater than the number required at another point. The arrangement of the arresters in the two cases was different, and this was doubtless the principal cause of the discrepancy.

Farley Osgood: Speaking as an operating engineer, I will say that the only time of the year during which we fear for the service is during the season of lightning storms. All other difficulties we seem able to overcome quickly and more or less easily. The record of our company shows that we have had a great number of interruptions due entirely to lightning, and that during a period of 15 months, with one exception, we had no breakdown of any apparatus whatever, other than that caused by lightning or its effects. I make this statement to bring before the engineers interested in the development of this apparatus the fact that it is the secret of the operating engineer's happiness. The operating engineer is held strictly to account for the number of interruptions, and his record is determined very largely by the number of interruptions which have occurred to the service during the year. He may be lucky and not have many; but it seems too bad that he must be held accountable for interruptions entirely beyond his control.

The record of our company, I think, brings before the members of the INSTITUTE the fact that damage from lightning is really our chief trouble. If the designing and manufacturing engineers are true to the ethics of their profession in the matter of giving the best advice to everybody, they will make every possible effort to become better acquainted with operating engineers, and instead of—not always, but quite often—forcing their ideas of apparatus upon the operating engineer, who sees only the practical end, they might listen to the suggestions of the operating engineer based on his practical experience, and combine it with their own theoretical work. Then we will get more speedy results. Judged by the papers which have been presented to-day this is coming about. I would like to ask Mr. Thomas, on account of the experiences which I related in my paper, which occurred during the year 1904, why the resistance in series with the gaps, the chief purpose of which is to limit the flow of the dynamic current, will not equally limit the flow of the static current.

P. H. Thomas: Briefly, in answer to the question of Mr. Osgood, it is true that the current of a static discharge, as well as the current from a generator, cause a potential upon a series resistance. Our only safety is in the possibility that the product of the amperes of the static discharge by the ohms in resistance shall not exceed the voltage which the insulation of the line and apparatus can withstand. This question can be determined only by experience on actual plants. As far as our experience goes, with such low values of series resistance as are used in the low-equivalent arrester as Mr. Scott has already stated, apparently we are on the safe side. I would make a possible exception of 50,000-volt and other very high-voltage plants.

H. C. Wirt: What is the resistance ordinarily used on an ordinary low-equivalent arrester?

P. H. Thomas: It depends on the voltage, and runs down to a few ohms on lower voltage; amounts less than a thousand on the highest voltages, if I remember correctly.

H. C. Wirt: I am sorry to say that my data on the low-equivalent type showed that at times they have failed, and it is for that reason I advocated trying the arrester without any resistance. I have also seen arresters of the same general type made with series resistance alone which have failed to protect. I think, therefore, the data which have been secured would seem to indicate that a very large number of cylinders in series, properly proportioned, will protect the system. I believe it is better to have a few short circuits in the arresters which did not at that time burn out the apparatus, than it is to put in series resistance without shunted gaps and throw the high-voltage effects into the apparatus.

E. E. F. Creighton: I think the answer to Mr. Neall's question can be stated briefly: the oscillograph is very limited in the frequency that it can measure. A few years ago I assisted M. Andraé Blondel in the development of the oscillograph. We reached 53,000 vibrations per second as a limit for the natural frequency of the oscillator. Damaging effects can be produced with frequencies greater than that. If the surge oscillations are as great as 50,000 per second, they can not be measured by the oscillograph.

THEORETICAL INVESTIGATION OF CIRCUIT CONTAINING DISTRIBUTED INDUCTANCE, SERIES CAPACITY, AND SHUNT CAPACITY, APPLIED TO THE MULTIGAP LIGHTNING-ARRESTER.

C. P. Steinmetz (by letter): Let, in a circuit containing distributed resistance, conductance, inductance, shunt and series capacity, as the multigap lightning-arrester Fig. 1, represented electrically as circuit in Fig. 2,

r = effective resistance per unit length of circuit, or per circuit element, that is per arrester cylinder.

g = shunt-conductance per unit length, representing leakage, brush discharge, electrical radiation, etc.

L = inductance per unit length of circuit.

C = series capacity per unit length of circuit, or circuit element, that is capacity between adjacent arrester cylinders.

C_0 = shunt capacity per unit length of circuit, or circuit element, that is, capacity between arrester cylinder and ground.

If then:

N = frequency of impressed e.m.f.,

it is:

Series impedance, per unit length of circuit:

$$Z = r - j(x - k) \tag{1}$$

Shunt admittance, per unit length of circuit:

$$Y = g - j b \tag{2}$$

where:

$$\left.\begin{aligned} x &= 2\pi N L \\ k &= \frac{1}{2\pi N C} \\ b &= 2\pi N C_0 \end{aligned}\right\} \tag{3}$$

or, absolute:

$$\left.\begin{aligned} z &= \sqrt{r^2 + (x - k)^2} \\ y &= \sqrt{g^2 + b^2} \end{aligned}\right\} \tag{4}$$

If the distance along the circuit, from line L towards ground G, is denoted by u,

the potential difference between point u and ground by: E,

the current at point u by: I,

the differential equations of the circuit are:[1]

$$\frac{dE}{du} = Z I \tag{5}$$

$$\frac{dI}{du} = Y E \tag{6}$$

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[1] Steinmetz, Alternating Current Phenomena, 3rd edition, pages 165 to 181.

Differentiating (5) and substituting (6) therein, gives:

$$\frac{d^2 E}{d u^2} = Y Z E \tag{7}$$

Intergrated by:

$$E = A_1 \varepsilon^{-\alpha u} + A_2 \varepsilon^{+\alpha u} \tag{8}$$

where:

$$a = \sqrt{Y Z} = a - j \beta \tag{9}$$

$$\left.\begin{array}{ll} a = & \sqrt{\tfrac{1}{2} \{y z + g r - b (x - k)\}} \\ \beta & \sqrt{\tfrac{1}{2} \{y z - g r + b (x - k)\}} \end{array}\right\} \tag{10}$$

Hence, substituting (10) in (8), and eliminating the imaginary exponents by the substitution of trigonometric functions:

$$E = A_1 \varepsilon^{-\alpha u} (\cos \beta u + j \sin \beta u) + A_2 \varepsilon^{+\alpha u} (\cos \beta u - j \sin \beta u) \tag{11}$$

It is, however, if:
n = total length of circuit from line L to ground G, or total number of arrester cylinders between line and ground, for:

$$u = n: \qquad E = O \tag{12}$$

and for:

$$u = O: \qquad E = e_0 = \text{impressed e.m.f.} \tag{13}$$

Substituting (12) and (13) into (11), gives:

$$0 = A_1 \varepsilon^{-\alpha n} (\cos \beta n + j \sin \beta n) + A^2 \varepsilon^{+\alpha n} (\cos \beta n - j \sin \beta n)$$
$$e_0 = A_1 + A_2$$

hence:

$$\left.\begin{array}{l} A_1 = \dfrac{e_0}{1 - \varepsilon^{-2\alpha n} (\cos 2 \beta n + j \sin 2 \beta n)} \\ A_2 = - A_1 \varepsilon^{-2\alpha n} (\cos 2 \beta n + j \sin 2 \beta n) \end{array}\right\} \tag{14}$$

and:

$$E = e_0 \frac{\varepsilon^{-\alpha u} (\cos \beta u + j \sin \beta u) - \varepsilon^{-\alpha(2n-u)} (\cos \beta (2n-u) + j \sin \beta (2n-u))}{1 - \varepsilon^{-2\alpha n} (\cos 2 \beta n + j \sin 2 \beta n)} \tag{15}$$

the Potential Difference against Ground.

From equation (5) follows, substituting (15) and (9):

Current:

$$I = -\sqrt{\frac{Y}{Z}} \{e_0 \varepsilon^{-\alpha u} (\cos \beta u + j \sin \beta u) + \varepsilon^{-\alpha(2n-u)} (\cos \beta (2n-u)$$
$$+ j \sin \beta (2n-u))\} \qquad 16)$$

Reduced to absolute terms, this gives:

Potential Difference against ground:

$$e = e_0 \sqrt{\frac{\varepsilon^{-2\alpha u} + \varepsilon^{-2\alpha(2n-u)} - 2 \varepsilon^{-2\alpha n} \cos 2 \beta (n - u)}{1 + \varepsilon^{-4\alpha n} - 2 \varepsilon^{-2\alpha n} \cos 2 \beta n}} \tag{17}$$

Current:

$$i = e_0 \sqrt{\frac{y}{z}} \sqrt{\frac{\epsilon^{-2\alpha n} + \epsilon^{-2\alpha(2n-u)} + 2\,\epsilon^{-2\alpha n} \cos 2\,\beta\,(n-u)}{1 + \epsilon^{-4\alpha n} - 2\,\epsilon^{-2\alpha n} \cos 2\,\beta\,n}} \tag{18}$$

and:

Potential Gradient, or *Potential Difference between Adjacent Cylinders:*

$$e^1 = k\,i = e_0\,k \sqrt{\frac{y}{z}} \sqrt{\frac{\epsilon^{-2\alpha u} + \epsilon^{-2\alpha(2n-u)} + 2\,\epsilon^{-2\alpha n} \cos 2\,\beta\,(n-u)}{1 + \epsilon^{-4\alpha n} - 2\,\epsilon^{-2\alpha n} \cos 2\,\beta\,n}} \tag{19}$$

For an infinite length of line: $n = \infty$, that is, for a very large number of lightning arrester cylinders, where $\epsilon^{-2\alpha n}$ is negligible, that is, in the case where the discharge passes from the line into the arrester, without reaching the ground, equations (17) (18) (19) simplify to:

$$e = e_0\,\epsilon^{-\alpha u} \tag{20}$$

$$i = e_0 \sqrt{\frac{y}{z}}\;\epsilon^{-\alpha u} \tag{21}$$

$$e^1 = e_0\,k \sqrt{\frac{y}{z}}\;\epsilon^{-\alpha u} \tag{22}$$

that is, are simple exponential curves.

Substituting (4) and (3) in (21) and (22) gives

$$e^1 = e_0\,\epsilon^{-\alpha u} \sqrt[4]{\frac{C_0^2 + \left(\frac{g}{2\,\pi\,N}\right)^2}{C^2 \left\{[1 - (2\,\pi\,N)^2\,C\,L]^2 + (2\,\pi\,N\,C\,r)^2\right\}}} \tag{23}$$

$$i = 2\,\pi\,N\,C\,e^1 \tag{24}$$

or, approximately, if r and g are negligable:

$$e^1 = e_0\,\epsilon^{-\alpha u} \sqrt{\frac{C_0}{C\left\{1 - (2\,\pi\,N)^2\,C\,L\right\}}} \tag{25}$$

$$i = 2\,\pi\,N\,e_0\,\epsilon^{-\alpha u} \sqrt{\frac{C\,C_0}{1 - (2\,\pi\,N)^2\,C\,L}} \tag{26}$$

Assuming, as instance:
$L = 2 \times 10^{-8}$ henry,
$C_0 = 10^{-13}$ farads,
$C = 4 \mathrm{x} 10^{-11}$ farads,
$r = 1$ ohm,
$g = 4 \mathrm{x} 10^{-6}$
$N = 10^8 = 100$ million cycles,
$n = 300$ cylinders,
$e_0 = 30{,}000$ volts,

it is:
(3): $x = 12.6$ ohm,
$k = 39.7$ ohm,
$b = 62.8 \mathrm{x} 10^{-6}$ mho,
(1): $Z = 1 + 27.1\,j$ ohm,
(2): $Y = (4 - 62.8\,j)\,10^{-6}$ mho
(4): $z = 27.1$ ohm
$y = 62.9 \mathrm{x} 10^{-6}$ mho,
(9): $a = 0.0021$
(10): $\beta = 0.0412$

(17): $e = 35{,}500\sqrt{\varepsilon^{-0.0042u} + .08\,\varepsilon^{+0.0042u} - 0.568 \cos (24.72 - 0.0824u)}$

(18): $i = 54\sqrt{\varepsilon^{-0.0042u} + 0.08\,\varepsilon^{+0.0042u} + 0.568 \cos (24.72 - 0.0824u)}$

(19): $e^1 = 2140\sqrt{\varepsilon^{-0.0042u} + 0.08\,\varepsilon^{+0.0042u} + 0.568 \cos (24.72 - 0.0824u)}$

Hence, at: $u = 0$:
$e = 30{,}000$ volts.
$i = 64.6$ amperes.
$e^1 = 2560$ volts.
at : $u = 300$:
$e = 0$
$i = 57.5$ amperes.
$e^1 = 2280$ volts.

With voltages per gap, varying from 2,280 to 2,560, 300 gaps would, by addition, give a total voltage of about 730,000, while the actual voltage is only about one-twenty-fourth thereof; that is, the sum of the voltages of many spark-gaps in series may be many times the resultant voltage, and a lightning flash may pass possibly for miles through clouds, with a total potential of only a few million volts. In above instance, the 300 cylinders include 7.86 complete wave-lengths of the discharge.

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THE SELF-SYNCHRONIZING OF ALTERNATORS.

BY MORGAN BROOKS AND M. K. AKERS.

The dexterity required for successfully connecting in parallel two synchronous machines, and the apprehension that is felt by the operator lest disaster result from the slightest inaccuracy of manipulation, have suggested a study of methods of synchronizing in the hope of diminishing the hazard involved.

When two alternators are controlled as to speed and excitation preparatory to closing the switch between them, it may not be possible to adjust the speed with sufficient exactness to allow reasonable time for closing the paralleling switch at the proper instant. If the switch be closed at or very close to the zero phase-position, and there be no appreciable speed-difference between the machines, no disturbance of the system is caused.

A moderate speed-difference is not serious, provided it is possible to close the switch at the proper moment, and automatic arrangements for so closing the switch have been devised. When there is a phase-difference, the existing vector difference in voltage is short-circuited through the two machines. The short circuit caused by closing the switch offers momentarily less impedance than the sum of the synchronous impedances of the two machines, because the resultant voltage cannot be in proper phase relation with the magnetic induction of both machines, and may not be with that of either. There will be an impulsive rush of current greater than one would be led to expect from dividing the vector difference in voltage by the synchronous impedances of the two machines.

The actual momentary current is governed by the resistance and the reactance of the armature windings considered as inductance without iron core, rather than by the synchronous impedance as ordinarily measured. The iron core has not time to become magnetized and to react against the applied voltage before great damage may have been done with even a moderate phase-difference. With large machines whose resistance and pure or non-iron reactance is relatively low, damage by even slightly inaccurate synchronizing will be more probable, as well as more costly, than with small machines, since the impulsive rush of current is proportionately greater. A moderate phase-difference such as 10° may be dangerous. If 10° (in either direction) be taken as the limit of safety, in closing the switch at random the chances will be seventeen out of eighteen that damage will be done.

We propose to eliminate this great chance for damage by making it safe to close the paralleling switch at any time, regardless of equality of speed or of excitation. It is evident that the maximum circulating current may be reduced in any desired degree by the insertion of sufficient impedance between the machines to be synchronized. It is equally evident that the synchronizing power, or force tending to keep the alternators in step, will be affected; and it remained for experiment to show that it is possible satisfactorily to limit the current, while retaining sufficient synchronizing power. No compelling force exists so long as phase-equality is maintained, and for small angles the force may be assumed to be proportional to the phase-difference.

Steinmetz has shown that the synchronizing power of the current that may circulate between two machines in parallel under the normal condition of equal voltage depends upon the lagging of the current due to the inductance of the short-circuit path through the armatures of the alternators. To retain this lagging current and its desirable effect, the impedance to be connected in series between the machines should be highly inductive. We tried various inductances such as transformer coils and arc-lamp regulators, but with indifferent success. If enough inductance were used to prevent too great an impulsive rush of current, the synchronizing current desirable at slight phase-differences was too weak. If the inductance was adjusted to get fair synchronizing power, it was not safe to throw the switch at a very much greater angle of phase-difference than without it. The range of safe angle was, however, perhaps doubled.

We next tried pure resistance, resulting, as might be expected, in loss of synchronizing power, since the circulating current did not have the required lag. The use of condensers in series confirmed the theory above outlined; for the alternators now assumed the 180° phase-relation, and retained it with such persistence as to suggest easy synchronizing by using a reversing switch to connect the machines together in the zero phase-relation. At this point we proved by experiment that it was a simple matter to synchronize two alternators through the armature of a third alternator not running, and then by bringing this third machine up to synchronous speed to observe that it automatically fell into step, forming a delta-connected, three-phase system. The oscillograph showed that with equal excitation the electromotive-force curves were properly spaced in 120°-positions, and that by varying the excitation it was easy to obtain a distorted delta of any desired shape, within reasonable limits, giving a simple means for obtaining any required vector-difference of voltage or current, especially if one of the machines were a polyphase machine but used as a single-phaser in a delta arrangement. The connection was fairly stiff, it being possible to cut off the driving power from two of the machines, when they became alternating motors and carried their previous driving motors as load. The oscillograph showed that the experiment was successfully performed.

Having control of the synchronizing angle at the 180°- and the 120°- positions we felt that some way to secure the desired 0°-angle must be available. A final idea of trying an inductance without any iron core came opportunely. This would secure the desired lagging current, and the pure inductance acting instantaneously would not permit an impulsive rush of dangerous value, even at maximum difference of phase. A trial met with flattering success; and by adjusting the amount of inductance we found that for a 7.5-kw. machine a value limiting the maximum current to about half its full-load amperes seemed the best, having due regard to objectionable reaction upon the system, as well as to synchronizing effect.

The experiments were tried at 60-cycle frequency, and the results were all that could be desired. We could close the switch paralleling two machines, while the machine to be brought into step was at a standstill, and then with approximate excitation it could be started and on reaching synchronous speed it would automatically fall into step smoothly, and with unexpected force, when the excitation could be adjusted and the inductance cut out.

It might be noted here that the circulating current between two machines connected together directly, and with a difference of phase-relation, is by no means equal to the current that would momentarily flow if the machines were switched together at the same vector-difference; that is, there is not the danger to the machinery in having two alternators pull apart, that there is in throwing them together with a large phase-angle. The almost non-inductive character of the synchronous impedance of two large alternators at the first moment of closing the switch is the critical point of synchronizing.

In the case of a synchronous converter, started from the direct-current side, the use of coreless inductance to permit the closing of the connecting switch at any instant is found to introduce a difficulty not present when the converter is otherwise started. This is the occasional tendency of the converter to race as a direct-current motor, owing to the weakening of its field and consequent increase of armature current. This objectionable tendency is easily overcome by the use of a second inductance connected in series with the direct-current armature and additional to the starting-box. This inductance should be with iron core, and it will act to prevent the rush of current due to any weakening of the field. This effect need be only momentary, as the converter does not tend to race; once forced into proper phase-relation. We found it desirable to have the speed of the converter brought into step slightly below synchronous speed, or at least not greater, when random closing of the switch was uniformly successful, as with synchronous generators. As this condition is a perfectly normal condition of operation it adds no complication. It may be stated that when synchronizing by means of condensers with the 180° phase-relation, there is no tendency for a converter to race with any reasonable difference of speed either above or below synchronism.

We believe the coreless inductance method of synchronizing particularly applicable to synchronous frequency converters, although we have had no opportunity of testing it. The inductances should be arranged for connection in series with both frequencies. Using a large inductance, or purposely regulating the speed so that the synchronizing power is not quite strong enough to enforce falling into step at either frequency alone, the combined synchronizing power of both sides will exert enough force to draw the machines into step promptly and with certainty. The customary slipping of one or more poles would not require positive manipulation of any kind. Some adjustment might be necessary to attain the best results.

We would not wish it understood that in using coreless inductances for safe synchronizing of alternators we recommend closing the switch at random. If the operator closes the switch as heretofore at approximately the moment of least disturbance, a refinement of operation will result. The operator will know that any error of judgment will at worst cause an almost imperceptible disturbance of the system, instead of a possible disaster. A considerable difference in the excitation of two machines will not interfere in any way, since the voltage can be adjusted after synchronizing. Relieved from all anxiety, the operator will work more easily, and score a higher average of perfect manipulations. Less time is needed and the use of a synchroscope is not required, the indications of the lamp being quite accurate enough. The proposed inductance may be connected either in the primary or in the secondary circuits of alternators as desired, and while its value in henries is different, the weight of wire in the coils would be approximately the same in either case; just as in a transformer the weights of primary and secondary windings are nearly equal.

The cost of a suitable coreless inductance is surprisingly small, since a high current-density may be employed, the heating effect is so evanescent. It is impossible for the machines to maintain a sensible vector-difference under normal conditions. Our tests indicate that a flat coil of large diameter for self-synchronizing need not cost more than one per cent. of the value of the machine to be synchronized, and one coil might be sufficient for an entire station. Considering the advantages of its use, the cost of such an arrangement is negligible. The inductance for use in the direct-current side of a converter to be synchronized is of the same order as for the alternating-current side, but it is not quite safe to predict its proper value.

Our experiments have been made with equal success upon various types of converters and alternators, including the inductor type. Dissimilarity of wave-form entails no difficulties. A certain hunting action that was always present with regular synchronizing in one series of tests was entirely absent with the new method. It is decidedly easier to connect in parallel two alternators by means of coreless inductance in series, than it is in direct-current operation to connect a second generator to the bus-bars. Our experiments have introduced the inductance in one phase only, although it evidently might be used in all phases, should such method offer any advantage. The behavior of alternators as exhibited in the oscillograph curves while self-synchronizing is beautiful to observe, and we regret that the recent success of the process prevents us from presenting photographic records of the curves at this meeting.

*A paper presented at the 23d Annual Convention
of the American Institute of Electrical Engineers, Milwaukee, Wis., May 23-31, 1906.*

MAGNETIC PROPERTIES OF ELECTROLYTIC IRON.

BY C. F. BURGESS AND A. HOYT TAYLOR.

Iron which has been deposited electrolytically from an aqueous solution is not necessarily a definite product, but varies in chemical composition and physical constitution, depending upon the adjustment of the various factors which govern the deposition. High purity is a property frequently ascribed to electrolytic iron, and it is probably a fact that by no other means can iron be purified to as high a degree as is possible by the electrolytic method. It is safe to say that absolutely pure iron has never been produced either electrolytically or by any other method.

The incentive which has led to a large amount of work on the electrolytic refining of iron is the need of a material of a high degree of purity to serve as a basis for the study of iron and its alloys. Until comparatively recently electrolytic iron has, however, been something of a curiosity, due to the difficulty of depositing it in anything but thin layers. Several years ago an investigation was undertaken in the applied electrochemistry laboratory of the University of Wisconsin, looking to the production of electrolytic iron in large quantities; and as a result it has been demonstrated that iron may be refined at a rate and a cost comparable to that existing in electrolytic copper refining. A further investigation of the production and properties of electrolytic iron, and of various alloys made from it, has been made possible by a grant from the Carnegie Institution of Washington. While working under this grant, nearly one ton of electrolytic iron has been produced, and plates one inch in thickness and weighing 75 lb. have been made. In following the question of a large scale production, particular attention was not given to the matter of purity, and as a result the iron which was produced did not equal the best grades of iron obtained on the market. But marked improvement has been made recently, the following analyses, for which acknowledgement is made to Mr. Andrew A. Blair, showing something of the degree of purity obtainable.

	No. 1.	No. 2.
Sulphur	None.	0.001%
Silicon	0.013%	0.003%
Phosphorus	0.004%	0.020%
Manganese	None.	None.
Carbon	0.012%	0.033%
Hydrogen	0.072%	0.083%

It may be noted that hydrogen is present in an amount greatly exceeding all the other impurities combined, and it is to the presence of this element that the characteristic properties of electrolytic iron are usually ascribed. It is well known that electrolytic iron as taken from the depositing solution is usually hard and brittle, and to such a degree that it may be crushed to a powder. Upon heating to a temperature of about 1 000° cent. and upward, it becomes soft and malleable.

The exact cause of this remarkable change of physical properties is not clearly apparent, though since some hydrogen has been observed to be given off during the heating operation, a relationship has been held to exist between the hardness of the iron and the hydrogen content. Some doubt is cast upon the existence of such relationship through the fact that similar amounts of hydrogen have been found in soft electrolytic iron which had been fused and in hard, brittle iron before fusion. The question is one calling for further investigation.

It is well known that the magnetic properties of electrolytic iron are altered to a great degree by heat treatment, and it is the purpose of an investigation now under way to establish the relationship between coercive force, permeability, hysteresis constants, etc., and the temperature at which the iron is heated. This paper is intended only as a short preliminary report on work which has been under way for some time, but which, owing to difficulties encountered in depositing and machining of the samples to be tested, has made but slow progress.

To prepare the test specimens necessary for the Rowland ring method of magnetic measurement, plates of electrolytic iron about one inch in thickness were deposited from a ferrous sulphate solution slightly acidified, containing also a small amount of ammonium sulphate. This deposition required about eight weeks. The resultant plate was ground smooth, and the ring was made from it by drilling and grinding, care being taken to prevent the metal from becoming heated. The first ring had to be rejected on account of a crack which developed in it. The first one upon which the measurements here described were made, had an average radius of 4.34 cm. and a rectangular cross section 1.158 cm. by 1.278 cm.

The primary winding of No. 18 wire was chosen to give a field strength of 20 dynes per ampere of primary current, and the secondary winding had 350 turns of No. 26 wire.

A Rowland D'Arsonval galvanometer whose calibration curve was accurately known, was used ballistically in obtaining the first hysteresis curves by the step-by-step method. The calibration curve of such a galvanometer is generally not a straight line, and this fact, combined with the change of the logarithmic decrement with various external resistances, renders the computations somewhat laborious, since the factor of reduction depends on the size of the deflections and on the total secondary circuit resistance. It has the advantage of having a definite control, not depending on the earth's magnetic field, and for this reason has tempted many to use it in connection with ballistic methods for magnetic induction. Unfortunately, in many cases the instrument is assumed to have a *constant*; that is, the factor to change from deflections to inductions is taken the same for all deflections. This is certainly not the case in many instruments of this type.

Later on in this work the Rowland galvanometer was discarded and a Nalder instrument of the suspended astatic needle type was used. This was provided with a thick laminated-iron shield to exclude external magnetic disturbances, and proved to be very satisfactory. The logarithmic decrement, or damping factor, was so small, even on closed circuit, that it could be neglected, and it was therefore not necessary to calibrate it with a standard solenoid, but rather with an Elliot condenser and standard cell.

One of the principal difficulties encountered was the elimination of errors due to *magnetic viscosity*. This is the slow but very appreciable change of magnetic induction which takes place some time after the change in field has been made, and hence is not taken account of in the galvanometer deflection. Thus an additive error is introduced in the step-by-step method, depending on the number of steps made. We very early discovered that the maximum induction as determined by this method did not agree with that obtained by the method of reversals, and much time was spent in running down the discrepancy, which is by no means peculiar to electrolytic iron. In fact this part of the work is the subject of a separate report by one of us, to be published a few months later. Suffice to say here, that the additive errors due to viscosity may be eliminated by the following modification of the step-by-step method.

The primary P of the test-ring (Fig. 1) is connected through

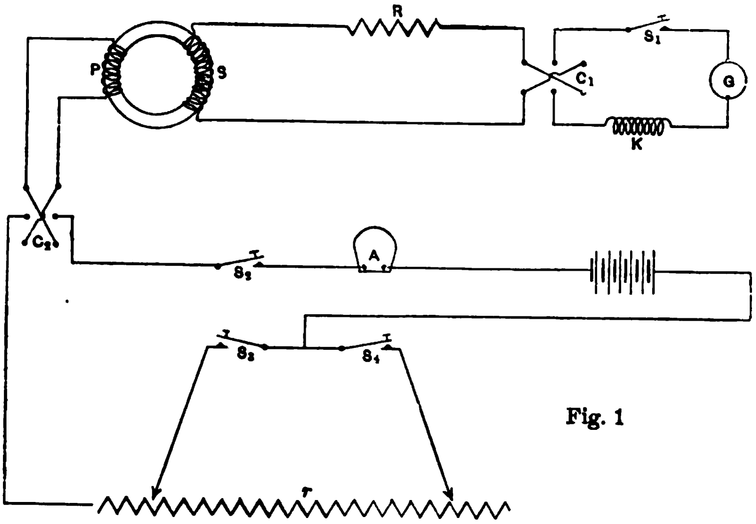
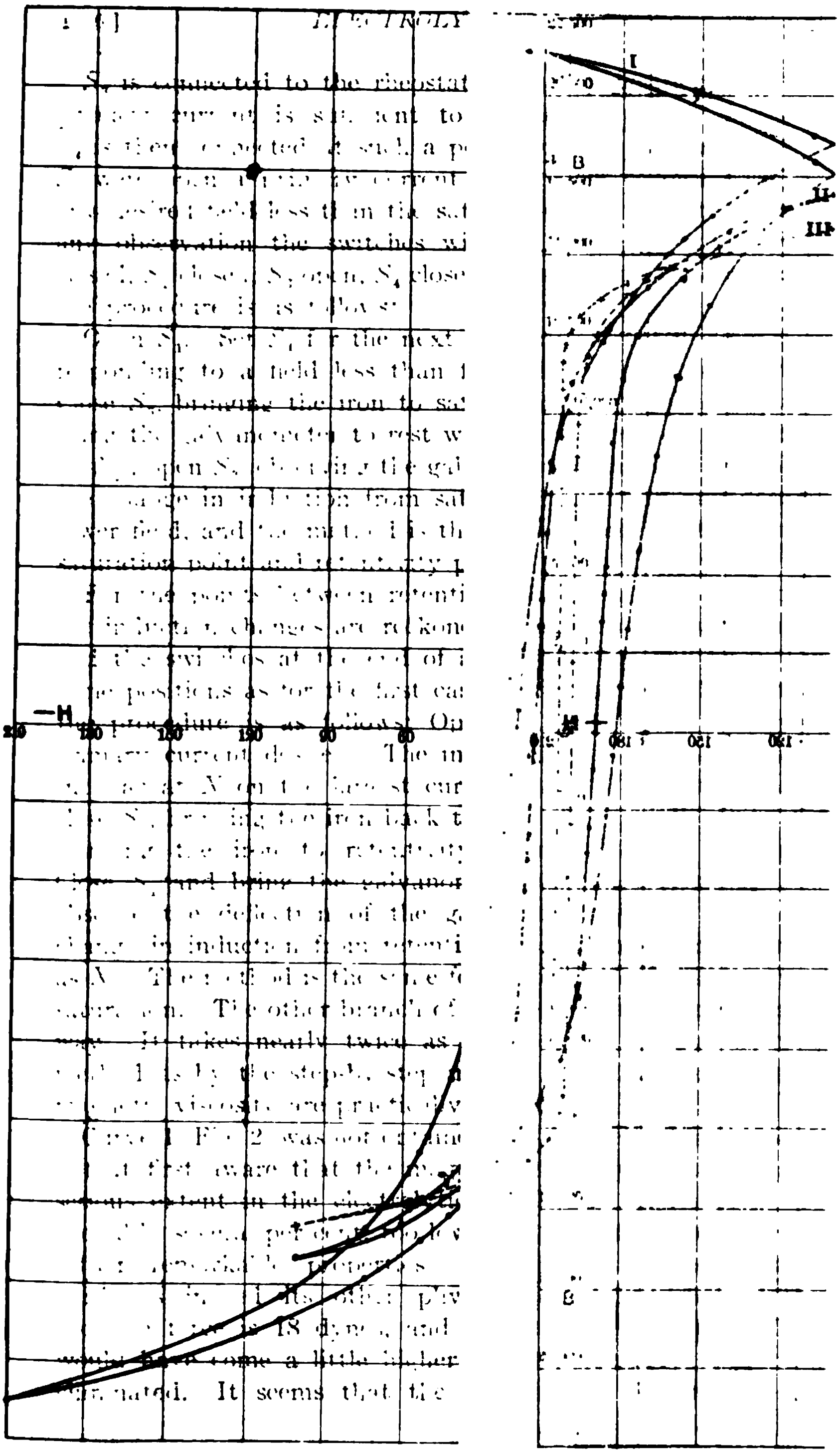


FIG. 1.

the reversing switch C_2 and the single pole switch S_2 with the storage-battery and ammeter A. The storage-battery is connected with a sliding contact wire rheostat, r, through the two switches S_3 and S_4, which have flexible leads with clips which can be attached to the rheostat at any desired point, The secondary of the test ring is connected through the resistance R_1, the switch S_1, the reversing switch C_1 and the control-coil K with the galvanometer G. This is the same scheme of connections used in the ordinary step-by-step method. The modification lies in the method of procedure, which for that part of the hysterises curve between saturation point and retentivity point is as follows:



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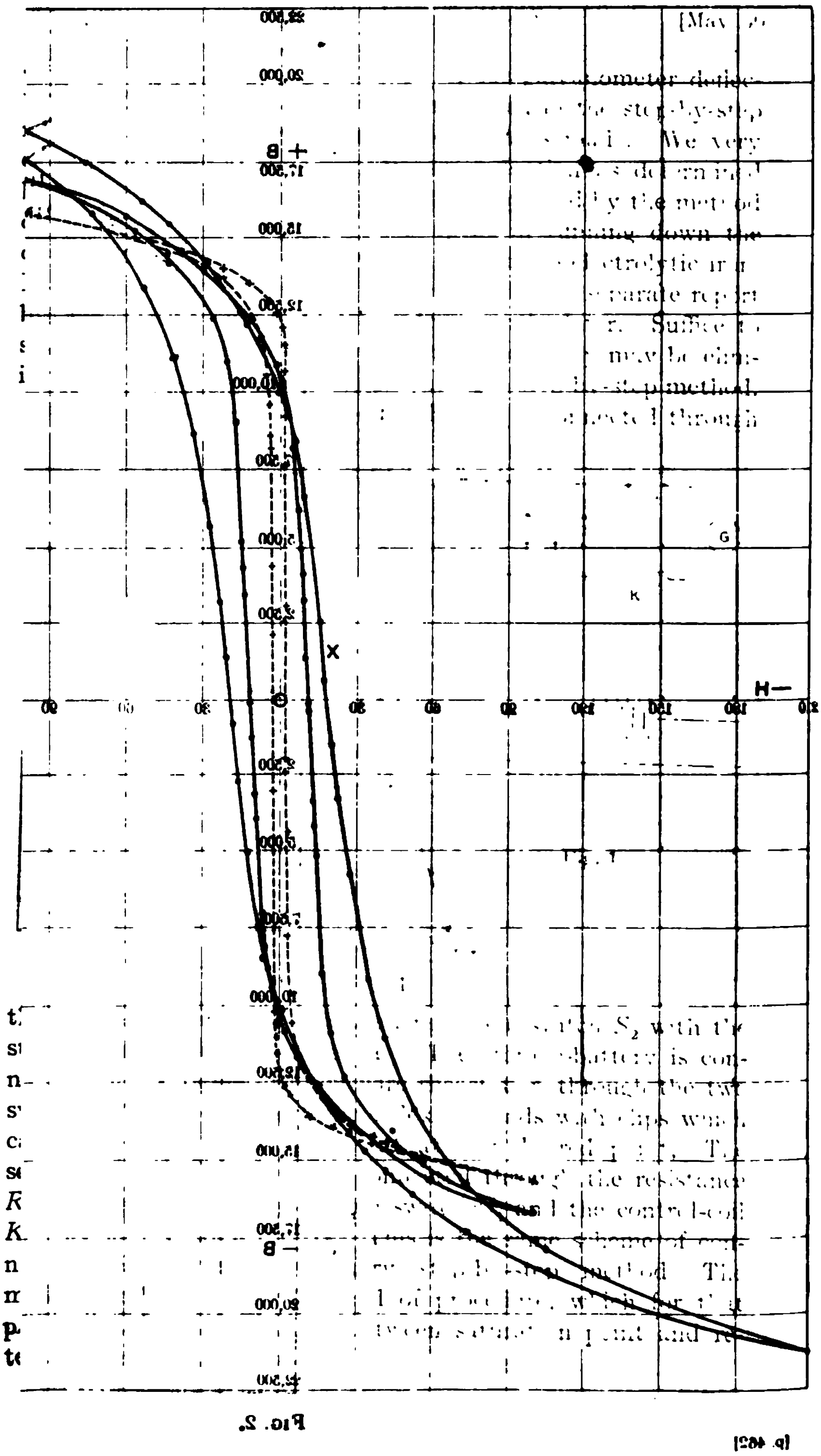
+B
−B
H—
X
G
K
22,500
20,000
17,500
15,000
12,500
10,000
7,500
5,000
2,500
0
20
40
60
80
100
120
140
160
180
200

Fig. 2.

S_3 is connected to the rheostat in such a position that the primary current is sufficient to produce a saturation field. S_4 is then connected at such a point on the rheostat that if S_3 were open a primary current would flow, corresponding to any desired field less than the saturation field. At the end of any observation the switches will be in these positions: S_1 closed, S_2 closed, S_3 open, S_4 closed. For the next observation, the procedure is as follows:

Open S_1. Set S_4 for the next primary current desired, corresponding to a field less than for the previous observation. Close S_3, bringing the iron to saturation point. Close S_1 and bring the galvanometer to rest with the control-coil K. Then finally, open S_3, observing the galvanometer throw. This gives the change in induction from saturation point to any desired lower field, and the method is the same for all points between saturation point and retentivity point.

For the points between retentivity and negative saturation the induction changes are reckoned from the retentivity point and the switches at the end of an observation will be in the same positions as for the first case. For the next observation the procedure is as follows: Open S_1. Set S_4 for the next primary current desired. The induction will have some value such as at X on the largest curve, Fig. 2. Reverse C_2, and close S_3, bringing the iron back to saturation point. Open S_2, bringing the iron to retentivity point. Reverse C_2 again. Close S_1 and bring the galvanometer to rest. Close S_2, and observe the deflection of the galvanometer. This gives the change in induction from retentivity point to any point such as X. The method is the same for all points as far as negative saturation. The other branch of the curve is done in the same way. It takes nearly twice as long to run a curve by this method as by the step-by-step method, but the errors due to magnetic viscosity are practically eliminated.

Curve 1, Fig. 2, was not obtained by this method, as we were not at first aware that the magnetic viscosity existed to any serious extent in the electrolytic iron. The values of B are probably several per cent. too low, but the curve shows several rather remarkable properties. The iron is evidently very hard, as indeed its other physical properties show. The coercive force is 18 dynes, and the retentivity 10 000. This would have come a little higher had the viscosity error been eliminated. It seems that the field of 210 dynes does not saturate the iron, although it carries the induction to the high value of 21 250. At the same time there is relatively little area added to the hysteresis loop by running the field so high.

It is known that heating causes the liberation of hydrogen from electrolytic iron, the evolution beginning at comparatively low temperatures and increasing as the temperature is raised. The test-ring was heated for several hours at a temperature of 200° cent., and magnetic tests again made. These gave a curve almost identical with the first, and showed either that it is not the hydrogen in itself which contributes to the magnetic properties of electrolytic iron or that the amount of hydrogen liberated was not sufficiently great to alter the magnetic measurements materially.

The ring was then unwound, embedded in magnesium oxide, and heated for eight hours at about 1 200° cent. In this process a small portion was corroded on one side, necessitating the turning down of the ring, and hence a different choice of windings. The ring was found to be much softer than at first, and on being tested by the step-by-step method, gave values for the magnetic induction 17% lower than those obtained by the method of reversals. As explained earlier in this paper, this was traced to magnetic viscosity, and a modified ballistic method was devised to eliminate the error. The dotted curve was obtained by this method, and comparison with the large curve shows that a tremendous change had taken place with the heating at 1 200° cent. The iron is now in the condition of a rather soft steel, with a coercive force of about 2.5 dynes, a retentivity of 12 500 and a large amount of magnetic viscosity in the steep parts of the curve. A second heating of the ring to over 1 200° cent. produced no appreciable change in the magnetic properties.

Another ring was prepared of electrolytic iron deposited from a solution maintained more nearly neutral than in the former case, the deposit being somewhat less hard and brittle and the fracture showing a finer crystalline structure. The mean radius of this ring was 4.175 cm.; the width of face 0.97 cm.; and the thickness 0.768 cm.

The primary turns were 418, and the secondary 350. The curve II was obtained from this ring by the modified ballistic method, and is evidently like curve I, except that the peculiarities are not so marked. A field of 100 dynes gives a maximum induction of 15 750, and a retentivity of 10 300. The coercive force is 11 dynes. The iron is still very hard, but its other physical properties also indicate that it is not so hard as the first sample.

After some further tests have been made on this ring it will be heated to various temperatures and tested, with a view of determining at just what temperature the area of the hysteresis loop begins to change rapidly.

Magnetic viscosity is usually found in rather soft steels, of low coercive force, or even in many samples of soft iron. It was therefore a matter of surprise to find that the step-by-step method gave values of the maximum induction for ring II 6% lower than those obtained by the method of reversals, and by the modified ballistic method. This indicates a considerable amount of magnetic viscosity. We hope to have some laminated annealed rings in the near future, and to continue this investigation with these and with some rod samples, as well as with the rings we now have.

DISCUSSION ON "MAGNETIC PROPERTIES OF ELECTROLYTIC IRON," AT MILWAUKEE, WIS., MAY 30, 1906.

E. F. Northrup: It is well known that if aluminum has alloyed with it a small per cent. of copper the electrical conductivity of the aluminum is lowered; the addition of a metal of better conductivity to aluminum thus reducing instead of increasing its conductivity. I would like to ask if Professor Burgess has found an analagous effect in which the permeability of pure nickel is decreased by the addition to it of a small per cent. of pure electrolytic iron, or, on the contrary, does the addition of iron to nickel increase the permeability of the nickel?

I would also like to inquire if he has produced all his electrolytic iron from wet solutions, or are there salts of iron which can be fused, and the iron deposited from them electrolytically when in a molten state?

I am naturally interested in his method of making measurements of permeability, and I am rather sorry to see that he has abandoned the use of so excellent an instrument as the D'Arsonval galvanometer. I think the D'Arsonval galvanometer, if properly constructed and properly used, is entirely reliable, and far more convenient than any other form of galvanometer when used for this kind of work.

The essential features that the D'Arsonval galvanometer should possess for this class of work are easily gotten. The damping should be electromagnetic, the shape and weight of the coil being such that the air damping is reduced to a minimum. The calibration of the galvanometer can be accurately made by means of a standard of mutual inductance, and the secondary of this standard should be permanently in circuit with the galvanometer and test-coil. Since copper changes about 0.4% per degree centigrade in resistance, the external portion of the galvanometer circuit should be not of copper but of manganin or other wire of nearly zero temperature coefficient. With these and other features of construction observed the constant of a ballistic D'Arsonval can be made very constant, and satisfactory sensibility can be obtained for permeability tests. Years of experience in working with both Thompson and D'Arsonval galvanometers has led me to prefer the D'Arsonval galvanometer for all classes of work except where the most extreme sensibility is required, as is the case when a bolometer is used.

The magnetic viscosity of which Professor Burgess has spoken is a very interesting property of the metal, and I would like to have him tell us, if he is willing, how it is explained on Ewing's theory of magnetism, and also what relation it bears to the "soaking in" of a condenser.

D. C. Jackson: This paper shows a small detail of some research that Professor Burgess has been doing. Professor Burgess has done a tremendous amount of work in an effort to produce pure electrolytic iron in large quantities, so that large samples may be tested and we may be able to find out what its individual qualities are. After having found that he could make what seemed to be pure electrolytic iron in quantities sufficient to handle, he became ambitious to make it in large quantities, great chunks, big cathodes, like those of electrically refined copper; in that process he has gotten to a point where the iron is not very pure. I presume an equal amount of energy will now have to be put into the research to come to these big cathodes while maintaining the deposited iron chemically pure. The discussion of that work may wisely some day come before this INSTITUTE. This may seem to some like a matter of purely philosophical interest, but after all, it may have a tremendous influence upon all the industries in which iron plays a part, including the electrical industries.

The metallurgy of iron and its alloys is purely a matter of rule of thumb at the present time, and that is largely due to the fact that it has been impossible to get pure iron in sufficient quantities to investigate and experiment with, so that we may discover what its characteristics are. It is with that in view that Professor Burgess has entered on this investigation, and I believe that he is going to get something very much worth while. This little feature which he brings before us to-day is a matter of side interest, on account of the magnetic test. I want to point out in this connection an element of interest. You will notice that the iron was deposited and the rings were then ground out of the deposit, directly from the cathodes. Of course that is done partly for the purpose of being able to test the iron as it comes in the deposited chunks, that is, without the effects of heat treatment; but I will add that I think Professor Burgess has not been able to melt the pure iron in sufficient quantities, and still keep it uncontaminated, to cast rings, and that is another one of the tremendous difficulties he is now working with. He has been using the heat of the electric furnace in order to supply the melting temperature, and to begin with he finds it necessary to work out new crucibles of refractory materials which will not deteriorate the iron.

I bring these matters to your attention with the purpose of giving you an idea of the magnitude of the work Professor Burgess is trying to carry on, so that you will not think that the magnetic testing of a few rings ground out of cathodes is by any means the limit of his extended and really magnificent piece of investigation which he has been carrying on for several years and probably will continue to carry on for a number of years.

Charles F. Scott: One of the attractive points of this paper is the reduced loss from hysteresis, and the possible application of the material in the construction of dynamos, transformers and the like. I notice that the curves are taken at a fairly high induction. I inquire whether the same ratio of losses prevails at lower induction as in the cases here taken? The amount of energy which is used in overcoming hysteresis in commercial apparatus probably runs into millions of dollars every year. This fact opens up the suggestion of a very important application for the improvement of electrical apparatus, if this kind of iron should be found amenable to the forms of construction necessary in electrical apparatus.

W. L. R. Emmet: I notice that curve 1 and curve 3 are made from the same sample, with very different characteristics. I would suggest that to make a sample out of an electrically deposited mass of iron would be a rather uncertain way of investigating its properties, inasmuch as it might not be homogeneous and certainly would not be in a commercially useful form. The simple process of heating changes it. I think the iron should be forged and worked to some degree equivalent to that required for practical use, so that the useful properties might be studied. We would be left to suppose that the differences of all these curves were caused by some mere mechanical changes in the arrangement of particles, and that this is not really a chemical study of the iron at all, but a study of the mechanical conditions.

C. P. Steinmetz: The only experience I have had with electrolytic iron was about 14 years ago, when investigating the hysteresis and permeability of iron. I used the same electrolyte, a sulphate of iron-ammonia solution, and used as negative mercury. This gave an amalgam containing about 11% iron. The magnetic analysis showed almost constant permeability of 2, and a high hysteresis loss. This amalgam of iron, heated for a considerable time beyond the boiling point of mercury, left a spongy mass of pretty nearly pure iron, which had the same characteristics as shown here: a very considerable hardness and a very large hysteresis loss, although hydrogen in this case could hardly be in the iron. In short, it represented hard and not soft iron.

The question of the magnetic properties of iron, as Mr. Scott has said, is very important for the electrical engineer, and since this is the only paper at the convention dealing with magnetism, I think it desirable to draw your attention to the great change in our conception of magnetism which is taking place at the present time, due to the work of the last few years.

We have been used to consider magnetic permeability as a property of a few selected materials—iron, nickel, cobalt, magnetite and oxygen. There is one oxide of chromium Cr_5O_9, which is strongly magnetic, comparable with magnetite, but difficult to get. In the last few years a remarkable alloy has been found, containing copper, aluminum, and manganese; in the percentage of 60 to 65 copper, 20 manganese, and the rest aluminum. This alloy shows a fairly high magnetic permeability. Manganese has never been considered as a magnetic material, and a small per cent. of manganese in iron spoils its magnetic characteristics. The manganese-copper-aluminum alloy acts almost inversely to iron. If iron is heated and suddenly chilled it gets hard and of low permeability. This alloy, as it is cast and slowly cooled, has low permeability, you can just notice the attraction by a magnet; but if it is heated and suddenly chilled the permeability is quite high, and still more so by melting it in a blast flame and letting it drop into water. I give you this preliminary statement; the exact data I must reserve for a future time. This alloy I should say is between magnetite and nickel, regarding its magnetic characteristics.

My attention has been called by Dr. Harden to a still more curious material. If about three parts antimony and one part manganese, powdered or coarsely granulated, are heated in a test tube, that is, to a moderate temperature, then the mixture which before was entirely non-magnetic, is strongly magnetic, while still apparently a loose powder, and shows the lines of force of a magnetic field, like iron filings. This has led me to investigate, and I have found that if antimony is melted in the presence of manganese it becomes magnetic to a somewhat less extent than magnetite; it has probably a saturation value of 3000 or 4000 lines per square centimeter; but even with such a very small quantity of manganese in the antimony that a rough qualitative analysis found no manganese, the antimony was quite strongly para-magnetic. I then tried zinc. I melted zinc and maintained it at a temperature fairly high above the melting point, in the presence of manganese, but it did not lead to any results, possibly because manganese is covered with an oxide film, and is not dissolved. But by carefully dropping a piece of manganese suddenly into the melted zinc, I succeeded in getting a small quantity of the zinc containing manganese which was strongly para-magnetic. I went further, and added sodium, melting zinc with a small percentage of manganese and sodium, the sodium acting as the reducing agent, and the zinc so dissolved manganese and formed a magnetic alloy. In looking over my samples I found a piece of manganese tin which had been lying on a shelf for years and it was quite strongly para-magnetic.

Herefrom it seems to follow that manganese is a magnetic metal, but is non-magnetic when free, but strongly magnetic in alloys. If the metal by itself could be made to exhibit the same permeability as pure metal as it has in alloy, it would be several times more magnetic and have a magnetic saturation several times higher than soft iron. That led me to the conclusion that in the copper, aluminum and manganese alloy, the aluminum is the reducing agent, which reduces the oxide film on the manganese, and so makes the copper dissolve the manganese. Therefore it follows that there are alloys which contain no iron, nickel, or cobalt but still have an appreciable permeability, and it is not impossible that there might be found alloys of metals which have permeabilities higher than iron. Obviously, it would be extremely valuable for the electrical engineer if something could be found more magnetic than iron. At the present time, however, in my opinion, there is no chance for that; but the whole field which opens up here regarding our views on magnetism is extremely interesting and worthy of further exploration.

I intend to give a paper on this subject, with some numerical values, but have not yet succeeded in finding the time fully to investigate the subject, particularly to determine the exact numerical constants, and so I give this statement as preliminary, and shall perhaps at some other time give further information. Perhaps somebody else may be willing to investigate further the magnetic qualities of manganese alloys.

C. F. Burgess: There appears to be no fundamental reason why iron may not be deposited from a fused bath as well as from an aqueous one, but no one appears as yet to have pointed out a suitable composition of fused salts for this purpose.

Magnetic viscosity is a property of iron which was recognized by Ewing.

The reasons for discarding the D'Arsonval galvanometer for the astatic needle type are covered in the paper, and for reasons more in detail the speaker begs to refer the matter to Mr. A. Hoyt Taylor who has made a special study of magnetic tests and who proposes to carry the study of the magnetic porperties of electrolytic iron through the coming year.

Whether hydrogen is held physically or chemically in electrodeposited iron is a matter upon which there is a difference of opinion and it has not been proved conclusively one way or the other. It is not unreasonable to suppose that it may be held both physically and chemically, from the fact that some of the hydrogen is liberated at the temperature of boiling water, while perhaps a greater part of it is held with great tenacity and is not expelled even when the iron is melted.

The question has been raised as to whether the ratio of the magnetic cycles for heated and unheated electrolytic iron is the same for low fields as it is for high ones. While tests have not been made to prove that the ratio is exactly the same, it is undoubtedly approximately so. The curves given in this paper do not show the results of the best samples of iron which have been produced, and in fact the permeability can be increased and the hysteresis reduced by suitable heat or chemical treatment. As to the suggestion that the tests would have been more complete had the iron been forged, it may be pointed out that it was not the purpose of the paper to deal with the magnetic properties of the melted or forged iron, although one hundred or more samples have actually been made from melted ingots. The magnetic properties of the forged iron are different from those of the iron heated as described, but as to what this difference may be due is a subject for further investigation.

To the very interesting information which Dr. Steinmetz has given relative to magnetic materials in which iron is not present, at least one additional compound may be mentioned. Dr. O. P. Watts found on carrying on an investigation of electric furnace products in the Applied Electrochemistry Laboratory of the University of Wisconsin that manganese boride, a definite compound free from iron, has striking magnetic properties.

R. A. Fessenden (by letter): The determination of the magnetic properties of electrolytic iron is of very great importance, not only from a commercial but more especially from a scientific standpoint. Professor Burgess' method of producing the iron enables us for the first time to obtain a sufficient quantity of the material for test. The grant from the Carnegie Institute will enable the work to be carried out, and we have therefore good grounds for hoping that Professors Burgess and Taylor may succeed in settling the question.

The methods used, as described in this INSTITUTE paper, are, however, entirely inadequate to give any accurate results. At least some dozen sources of error have not been taken into consideration. For example, the dimensions of the rings used would absolutely prevent any correct results being obtained, since the value of H on the outer edge of the ring is 25% greater than that on the inner edge of the ring, and any curves obtained would therefore be merely composites of a number of curves for a range of H varying 25%.

Before taking up this work, it would be advisable to consult the literature on the subject for the purpose of eliminating sources of error. A brief list of the majority of these has been given by the writer in a paper on " The Nature of the Electric and Magnetic Quantities," *Physical Review*, February, 1900. Also the papers of Hopkinson and others on the rate of decay of magnetization in solid bars, should be consulted. As a matter of fact, it is doubtful whether it is worth while making any experiments on solid rings, as there is no known and practicable way in which the effect of interior eddy-current lags can be eliminated, and probably correct results can only be obtained from rings made from thin, laminated, carefully insulated sheets, or radius large in comparison with the thickness of the torus, and carefully wound to prevent magnetic leakage.

I call attention to these sources of error for the reason that the present opportunity on account of the ability of the gentlemen engaged in the work, and other favorable circumstances, offers such an excellent opportunity of settling the question once and for all that it would be a matter of regret if all errors were not eliminated.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

MEASUREMENT OF TEMPERATURE BY ELECTRICAL MEANS.

BY EDWIN F. NORTHRUP.

The measurement of a physical quantity implies, generally, the numerical comparison of the quantity with a certain selected quantity of the same kind taken as a unit. Temperature, however, can not be treated as a quantity in the same sense. It is rather to be considered as a state in which matter is found, and all temperature measurements are made by comparing the changes produced by heat in some form of matter. As shown by Lord Kelvin as early as 1848, temperature may be expressed on a scale which is independent of any particular form of matter, but this thermodynamic scale can not be used in actual temperature measurements, which, in practice, consist in comparing the changes in some particular forms of matter produced by heat.

Certain gases change in volume under constant pressure or change in pressure under constant volume in a nearly regular manner with equal increments of temperature, as estimated on the thermodynamic scale. Gas thermometers have, therefore, naturally been chosen as standards with which to compare the changes in various forms of matter, which changes may then serve as a convenient means of temperature measurement.

It is probable that all matter exhibits more or less change with even slight temperature variations. Upon no physical phenomenon are human affairs more dependent than upon temperature and its relatively small natural variations. It is owing to the fortuitous circumstance that our planet now continues at about the one twenty-fifth of its probable past temperature that life as we know it can exist. But only in the last century has the science of thermometry become clearly understood. Its principles are now well known, but it still needs to be further applied in our scientific enquiries and in many of our industries which are largely dependent upon it. Recent developments in producing immense ranges of temperature, from the cold of solid hydrogen, where the last motions have been nearly extracted from it, to the all-matter fusing heat of the electric furnace, have called for many new developments in the science and art of thermometry. It is now recognized that many industries, as the making of iron, porcelain, and glass, and many chemicals, can be greatly improved by using methods for accurately measuring temperatures. A knowledge and control of the temperature of storage places, as of grain, tobacco, ice, food-products, and the like, is often required. This puts a demand upon thermometry of measuring the temperature in one or many places, but observing or recording it in a place which is distant from where it is taken.

These and many other requirements have demanded and obtained, quite recently, an increase in methods, a refinement in precision, and an extension in range of temperature measurement.

The whole science of thermometry, especially if extended into high temperature pyrometry, is far too extensive to receive even a superficial treatment in a paper of this kind. Experiments and experience, however, have shown that the changes produced in electrical resistance by temperature and the thermoelectrical forces which it develops give, in the ranges over which the methods apply, the most delicate and simple means of temperature estimation.

The treatment of temperature measurement falls, therefore, into the province of the electrical engineer, and it is only the electrical methods of measuring temperature that will be considered here.

ELECTRICAL RESISTANCE THERMOMETRY.

Electrical resistance thermometry is possible because very many electrical conductors change in resistance with change of temperature in a perfectly definite manner.

The percentage change in resistance of the pure metals with temperature is a larger change than the percentage change in volume of gases, and over twenty two times as great as the volume change in mercury. Thus, the coefficient of expansion of nitrogen gas is 0.0036738, and of mercury, 0.000180, while the coefficient of increase of resistance of pure nickle is about 0.0041 per degree cent. between 0° and 100^c cent.

A change in electrical resistance can be measured with greater ease and far greater precision than a change in volume of a liquid or a gas. A change in either a high or a low electrical resistance can very easily be measured when it is one part in a million. Thus, the sensitiveness of the electrical resistance method of measuring temperature is very great. In the use of the bolometer, where the electrical resistance method of measuring temperature is carried to its greatest delicacy, temperature changes as small as one ten millionth of a degree cent. are said to be easily detected.

For the electrical resistance method of measuring temperature to be of general value, the resistance which is measured must always return to the same value when brought back to the same temperature. Fortunately, experience has shown that when the proper resistance materials are chosen, and proper precautions in their treatment have been used, the reliability of the method in this respect is very satisfactory. A properly constructed resistance thermometer if not exposed to too high a temperature will maintain its calibration better and longer than the best mercury thermometer, which is usually subject to small alterations and irregularities.

Curves which express the change of resistance with change of temperature of most pure metals all point at a low temperature to the zero of the absolute temperature scale. For a time this seemed to indicate that the resistance of the pure metals would vanish at the absolute zero of temperature. Later experiments made by Dewar at the temperature of liquid hydrogen, −252.7° cent., showed that the above conclusion was not justified, as at this low temperature the several resistances measured all tended to become constant.

As the pure metals are greatly elevated in temperature, the rate of increase in resistance with temperature also becomes less and less. Thus, over extensive temperature ranges, there are no metals of which the resistance is even approximately a linear function of temperature. Small impurities in the pure metals effect also the amount as well as the law of their change.

These facts make it unlikely that an electrical resistance temperature scale will be found bearing such definite relations to the absolute temperature scale as conveniently to serve for a standard scale of reference in the same manner as does the scale of the gas thermometer. When, however, the means are available, it is relatively easy to determine experimentally the relation between the electrical resistance of any particular specimen of wire and the temperature throughout the working range of the gas thermometer, if this does not exceed 900° or 1 000° cent. An electrical resistance thermometer can then be made of this specimen of wire, and it will serve as a standard with which other resistance thermometers may be very simply and easily compared.

The law of variation of electrical resistance with temperature in the case of platinum has been investigated by Callendar and Griffiths, and several others.[1] In this work it is shown that in the case of platinum the following relation exists between the temperature t, as measured on the air thermometer and the resistance of the platinum.

Let p_t be a temperature as defined by the relation

$$p_t = \frac{R_t - R_0}{R_{100} - R_0} 100,$$

where R is the resistance of a given specimen of platinum at 0°, R_{100} at 100°, and R_t at t°, all measured on the centigrade scale. It is then shown that placing

$$t - p_t = \delta \left[- \frac{t}{100} + \left(\frac{t}{100} \right)^2 \right]$$

expresses the difference between the platinum temperature as above and the temperature as measured on the air thermometer. This " difference formula," as it is called, holds to within 0.1° cent. up to 500° cent., and within 0.5° cent. up to 1 000° cent. In this formula δ is a coefficient which varies with the particular specimen of platinum used. For very pure platinum it is about 1.5, and larger for impure specimens. To determine δ the resistance of the thermometer is measured at the three known temperatures, 0° cent., 100° cent., and 444.5° cent., the boiling point of sulphur. The authors referred to give convenient methods of using the difference formula to convert the tem-

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[1] A full treatment of this subject is to be found in Chapter V of the excellent work entitled "High Temperature Measurements," by H. Le Chatelier and O. Boudouard, and translated by G. K. Burgess.

peratures as given by the platinum resistance temperature scale to degrees centigrade as given on the scale of the air thermometer.

To engineers and those who have to make actual use of resistance thermometers the theoretical side of the subject is of small interest. There is a practical procedure which may be adopted that makes it unnecessary for manufacturers or users to give consideration to these methods of standardization of resistance thermometers. The instrument maker may carefully construct a resistance thermometer to serve as a standard and send this from time to time to the National Bureau of Standards at Washington. The bureau will measure the resistance of this thermometer at several known temperatures, over a wide range, which are given by their standard resistance thermometers, and furnish a certificate giving the relations that are found between temperatures and resistances of the thermometer submitted for calibration. The instrument maker may then use this thermometer as a standard with which other thermometers are easily calibrated. This is done by direct comparison in an oil bath for medium temperatures, and in a specially constructed electric furnace for high temperatures. Cold brine, or other means, may be used for making the comparison at low temperatures.

The feature of paramount importance in the use of electrical resistance thermometers is the constancy with which they maintain their calibration. This subject has received considerable attention, especially in the case of thermometers made of platinum wire, and the results observed have proved the entire reliability of this material for temperatures not exceeding 800° cent. or 1 000° cent. It is highly probable that other materials will behave in an entirely regular manner if not subjected to too high temperatures.

Careful investigations of the constancy of other materials than platinum, that are suitable for resistance thermometers, are greatly needed. But the investigations so far made show that where permanent alterations in resistance occur they may usually be traced to causes which proper precautions may avoid. Thus, the material selected for the thermometer may by nature be of an unstable character. Iron, for example, is an unsuitable metal to use. The material may contain impurities which by vaporization, crystalization, or otherwise, cause the resistance to alter gradually. The wire of which the thermometer is made may have been subjected to mechanical strains which gradually work out with repeated heatings, thus altering the resistance. If the material is one which does not oxidize, it may still be greatly affected at high temperatures by absorbing gaseous impurities. Thus, a nickel- or a platinum-wire thermometer heated to 400° cent. in a brass tube is ruined by absorbing the metallic vapors given off. For the same reason, all metal solderings near the resistance wire are liable at high temperatures to give off vapors which affect the permanent resistance, besides endangering the formation of local resistance at the joints.

Proper construction and choice of materials can remove all the above causes of permanent alterations. It may be that in the case of platinum, to some extent at least, and more so in other materials, slow permanent alterations in resistance occur, the cause of which is not known. Only extended investigations can give the limits of these possible alterations. Enough work has been done, however, to show that for even very refined work the reliability of platinum and some other materials is sufficient, if too high temperatures are not used.

In resistance thermometry, practical details of construction are all important. The chief of these will now be considered.

CONSTRUCTION OF RESISTANCE THERMOMETERS.

The best material of which to construct a resistance thermometer depends upon the temperature range to be measured, as well as upon the physical qualities of the available materials.

Constancy of composition and other practical considerations seem to limit the choice to a few of the pure metals, usually in the form of wire. The metal which has received the most study is platinum. It can be used over a very wide temperature range, and can be obtained under the name of Heræus platinum in a state of great purity. This material answers every requirement of resistance thermometry, except that it is very costly. A substitute for platinum should, therefore, be sought and used wherever it will serve as well. This substitute should be inexpensive, and obtainable in a pure state. It is desirable that it should have a high specific resistance, combined with a large temperature coefficient. It should be unoxidizable under usable conditions, and withstand a high temperature without deterioration or permanent alteration in resistance.

An examination of the pure metals shows that these conditions are best met by nickel. The writer has had many thermometers constructed of this wire for temperatures ranging from – 40° cent. to 300° or 400° cent., and has found it entirely reliable for this range. Conclusive experiments made to determine the availability of nickel for high temperatures would be very useful. It has a higher coefficient than the purest platinum, nickel being about 0.0041 per degree between 0° cent. and 100° cent., and pure platinum, 0.0039, and commercial platinum but about 0.002. The specific resistance of pure nickel and pure platinum is in the ratio of about 933 to 1 000.

It may here be remarked that a determination of the temperature coefficient of the metallic elements offers usually a very delicate test of their purity, and specimens of nickel and platinum which show a low temperature coefficient can positively be considered as impure and inferior for use in resistance thermometers.

Another test of interest, especially on wires intended for use in thermo-couples, is to attach the two ends of a short length to the terminals of a very sensitive galvanometer, and to pass a flame along the wire. If the galvanometer gives positive and negative deflections of considerable magnitude, the wire may be known to be unhomogeneous, and liable to have parasitic currents set up in it when exposed to high temperatures. A pure nickel and a pure platinum wire should show little of this effect.

The particular purpose for which a resistance thermometer is to be used largely determines its special features of construction. Broadly classified, resistance thermometers are particularly useful in the following cases:

1. Measurement of all temperatures below – 40° cent., the freezing point of mercury.
2. Measurement of all temperatures up to 1 000° cent., when the temperature is to be taken at a place where it can not be directly observed.
3. Measurement of temperatures below 1 000° cent., and above the range of the mercury thermometer.
4. Measurement of all temperatures below 1 000° cent., which have to be photographically or otherwise recorded.
5. Where small temperature differences or variations are to be determined for which the mercury thermometer is not sufficiently sensitive.

It is evident from such a classification as the above that there can be no general form or type of construction of a resistance thermometer. Each special requirement must be met by the instrument maker, who must be guided in his designs by experience and a study of the conditions. The form of thermometer having been chosen, the particular method of reading the resistance variations and of expressing them in degrees should have particular care, for in nearly every case which arises different requirements have to be met.

Resistance thermometers for use below 140° cent. are of relatively simple construction, for in this case silk-insulated nickel wire may be used. Certain precautions, nevertheless, need attention. The mass of the wire used and that of the body on which it is wound should be small, or the temperature of the resistance wire will lag behind any changing temperatures which are being measured, and lead to erroneous indications. The wire must be so chosen in respect to size and resistance that the heating of the wire by the needed measuring current shall be entirely negligible.

The constancy of any wound resistance depends largely upon the treatment to which it is subjected after being wound. The winding of the wire introduces strains, which gradually work out, causing variations in the permanent resistance. This certain result is avoided by an artificial aging, which consists in maintaining the wire, before the thermometer is calibrated, at a temperature higher than that at which it will be used, for several hours or days.

It is needful to end off the terminals of the wire, especially if short, in such a manner that no local variations in resistance can occur at the joints. As a rule the terminals should be hard-silver soldered for low-temperature thermometers, and for high-temperature thermometers all joints exposed to the high temperature must be welded joints.

Generally, the resistance wire needs to be protected by a casing. When, however, as in the measurement of moderate temperatures of gases or insulating fluids, the wire can be directly in contact with whatever is to have its temperature determined; the resistance thermometer assumes the surrounding temperature very quickly, far surpassing the mercury thermometer in this respect. If a casing must be used, it should be so shaped that the ratio of its surface to its volume is large, and the construction should aim to reduce to a minimum the heat which conducts along the case or which is distributed by air convection within it. Reproductions are here given of three types of resistance thermometers designed for the measurement of low or moderate temperatures.

The thermometer shown in Fig. 1 was constructed for use

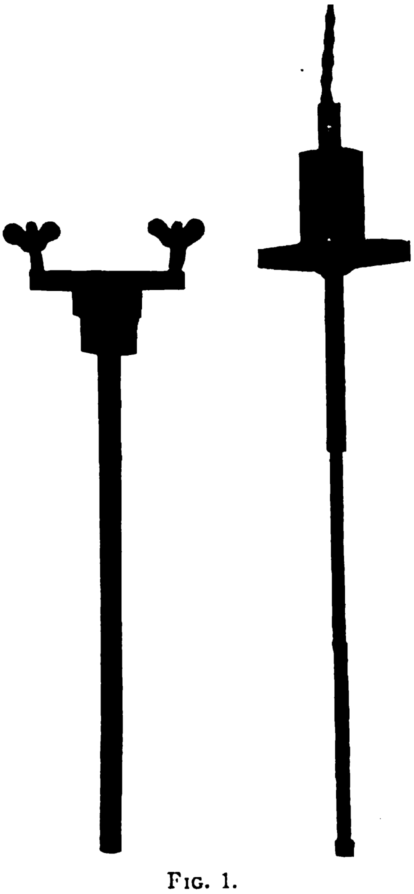

Fig. 1.

in measuring and recording with great precision the temperature differences between two brine mains. The average temperature of the brine was about − 37° cent., and the average difference of temperature between the two mains was about 1.5° cent. The allowable error was 0.01° cent., and hence great care in the construction of the thermometers, as well as in the rest of the apparatus, was required. This thermometer was wound with No. 35 platinum wire, of great purity. Its resistance at room temperature was about 80 ohms. It is probable that nickel wire would have served as well, but because of the better known properties of platinum and the importance of the experiment platinum was selected.

It should be noted that the steel case is long, and small in diameter, that the winding ends well below the nut which screws into the brine main, and that the wire is wound on a light frame of micanite, having a minimum of mass. A small sudden change in the temperature of the brine was followed by the thermometer to within about 0.005° cent. within two minutes.

Fig. 2 is a sectional view of a form of resistance thermometer made for the purpose of measuring the temperature of the soil at different depths where the thermometers are permanently buried. The winding is in the form of a skein, and No. 35 silk-insulated nickel wire is used. To insure permanency, the wire should be kept immersed after winding in hot paraffin for three or four days. The changes in the temperature of the soil are very slow, and hence there is no need to provide against a temperature lag of the thermometer winding.

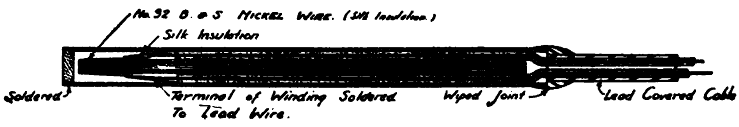

Fig. 2.

The resistance is made large, about 90 ohms at 20° cent., and the winding is encased in a brass tube filled with paraffin. The lead-covered leads are soldered with a wiped joint to the brass tube, thus preventing the entrance of moisture, which has to be carefully avoided. The resistance of the thermometer being high, the changes in the resistance of the leads is entirely negligible.

A similar construction would be suitable for measuring the temperature of the interior of stored material, such as grain, tobacco, hay, wheat, etc., also for measuring the temperature of cold-storage rooms. Any number of such thermometers can be located at different places, and be connected by a switch, one at a time, to a single reading device which reads directly in degrees fahrenheit or centigrade. The methods of reading these and other resistance thermometers will be presently described.

A and *B*, Fig. 3, are reproductions of two forms of platinum resistance thermometers designed to measure the temperature

FIG. 3.

of superheated steam under considerable pressure. In form *A*, the winding is directly exposed to the heated steam, while in form *B*, the winding is protected in a thin steel bulb. The stem of this latter form is made of small diameter to reduce to a minimum loss of heat by conduction. These thermometers were designed to read temperatures to about 300° cent.

Resistance thermometers give the most accurate and convenient means of measuring high temperatures up to 1000° cent. or possibly more. It is stated by Le Chatelier[1] that experiments carried out at the National Physical Laboratory, England, showed that throughout the temperature range of 1 000° cent. the agreement between the scales of the platinum-resistance and the thermo-electric pyrometers tested was within 0.5° cent. Le Chatelier adds, page 106:

> These results confirm the view of the sufficiency of the difference formula
>
> $$\left\{ t - p_t = \delta \left[-\frac{t}{100} + \left(\frac{t}{100}\right)^2 \right] \right\}$$
>
> for the most accurate work up to the upper limit of the safe use of the platinum-resistance thermometer.

The upper limit referred to is about 1 000° cent.

Such statements as the above, however, are true only when the resistance thermometers have been constructed in a particular manner to avoid alterations and deteriorations in the wire that are sure to result at high temperatures with improper construction. Platinum heated red hot and exposed to certain gases, as hydrogen or metallic fumes, absorbs impurities which permanently alter its resistance, and often render it extremely brittle. The writer unwittingly ruined both a platinum and a nickel thermometer by exposing the wire encased in a brass tube to a red heat. The fumes of zinc given off were absorbed by the resistance wires, rendering them so brittle that they fell to pieces when lightly touched.

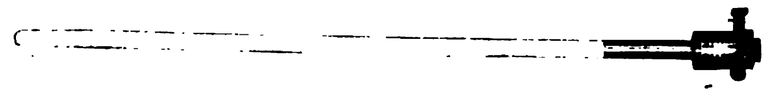

Fig. 4A.

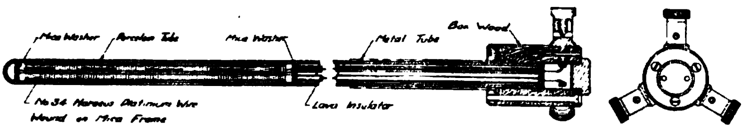

Fig. 4B.

Accumulated experience has shown that for temperatures over a red heat the design of the thermometer should embody the general features shown in the illustration, Fig. 4, *A* and *B*.

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[1] "High Temperature Measurements," page 105, 1904 edition.

In the thermometer here illustrated, the winding is a pure Haræus wire, its purity being shown by its temperature coefficient, which is about 0.0039° at 100° cent. This wire, No. 35 B. & S., is wound bare, by a special machine process devised by the writer, on a frame of thin mica, in such a manner as to touch only the edges of the mica. The winding is 36 turns to the inch. The mica frame is made by matching together at right angles two pieces of mica sheet, of the shape shown in Fig. 5.

As the winding touches at the edges of the mica only, but a small percentage of its length can become contaminated by any possible action of a solid material. The lead wires, by a method of compensation to be later described, do not enter into the resistance which is measured, and may be of a cheaper grade of platinum than the resistance winding. These lead wires are either three or four in number, according to the method of compensation adopted. They are insulated from each other by being passed through tubes of porcelain and mica washers. The mica washers serve the additional purpose of preventing the free circulation of air from the hot end to the cooler top of the thermometer tube.

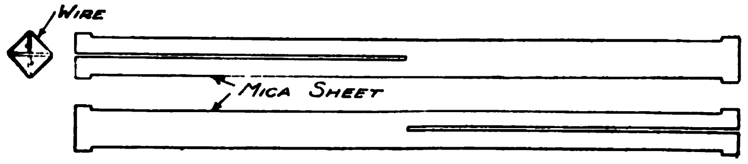

Fig. 5.

For temperatures above the fusion point of hard glass, porcelain tubes especially constructed for this work by the Berlin Porcelain Works are the most satisfactory material for a casing.

The interior parts of the thermometer shown in Fig. 4, *B*, are designed to be easily withdrawn from the tube for examination, and again replaced. In the particular case shown, the winding was made 5.25 in. long, so as to give the thermometer a high resistance. This is generally an advantage, where the conditions permit, as the contact resistances in the measuring device are then small in comparison, and greater sensibility of the galvanometer used is more easily obtained.

It was legitimate to make the winding long for the case shown, as this thermometer was designed to measure the temperature of hot gases which surround the porcelain tube more than half way to its head. If, however, the temperature of the place to be measured is uniform over a small space only, then the winding should be as short and as much concentrated at the end of the tube as possible, and thus permit of placing the entire winding in the hot place, the temperature of which is to be measured.

Thermo-couples, to be later spoken of, have in this respect an advantage over a resistance thermometer as above designed; for the end of the thermo-couple is a very small body, that may be placed at the exact point of a space where the temperature is to be observed. This consideration has led the writer to design another form of resistance thermometer which will be shown to combine the advantages of both. A description of this is best given, however, under methods of reading resistance thermometers, which we shall now consider.

METHODS OF READING RESISTANCE THERMOMETERS.

As the National Bureau of Standards at Washington will furnish the instrument maker with a certificate giving the connection between the electrical resistance and the temperature of a selected standard resistance thermometer, the calibration of other thermometers is reduced to comparing their resistances with those of the standard when all are brought to equal temperatures. In the case of high temperatures, a specially constructed electric furnace is used for the purpose. The problem, then, of reading temperatures with thermometers thus calibrated resolves itself into measuring their resistance in a simple manner when subjected to different temperatures.

The resistance being known, the temperature may be taken from a previously plotted curve, or the resistance-measuring device may be constructed to read directly in degrees centigrade or fahrenheit. The convenience, simplicity, precision, and reliability with which these measurements can be made largely determines the practical and commercial usefulness of resistance thermometers. The continuous recording of temperatures given by resistance thermometers, as well as thermo-couples, is another, but closely related problem, that will receive some of our attention

The available and useful methods of determining resistances to measure temperatures may be classified as follows:

a. Slide-wire bridge methods.

b. Use of dial or decade wheatstone bridges.

c. Kelvin double bridge methods.

e. Direct deflection method, the electromotive force being maintained constant.

f. Direct deflection method, being independent of voltage by using the writer's new instrument, called a ratiometer.

a. SLIDE-WIRE BRIDGE METHODS.

This is a very convenient zero method to employ, especially when the reading instrument has a scale calibrated to read directly in degrees. The slide-wire bridge may have its connections arranged in either of two useful ways. The first is less precise, but more convenient. The connections are given diagrammatically in Fig. 6.

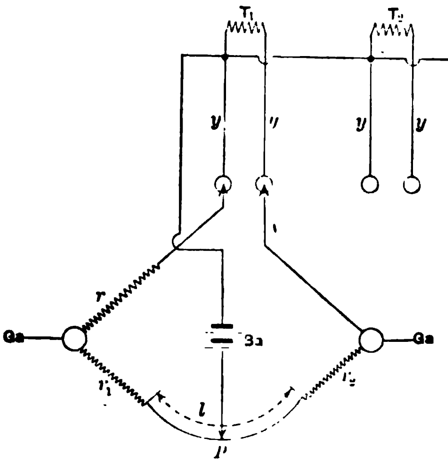

FIG. 6.

T_1, T_2, T_3, etc., represent any number of resistance thermometers, y, y, are the thermometer leads which should be alike, but may be of any length. Contact can be made with any thermometer by means of a simple sliding switch. The resistances, r, r_1, r_2, should be about equal to each other and to the resistance of the thermometer at a mean temperature.

The resistance of the slide wire, *l*, should be such as will take care of the variation in resistance only, of the thermometers.

In the actual construction, the contact, *p*, would move over a circularly disposed wire and scale. This scale may be divided into arbitrary divisions, and reference be made to a curve, to obtain the temperatures of any thermometer corresponding to a given setting for a balance. In this case, the different thermometers only need to be made of approximately the same resistance. The scale may, however, without great difficulty, be graduated to read directly in degrees when used with a thermometer of a particular resistance and temperature coefficient.

If, however, many thermometers are to be read on the same scale, they must be adjusted to exact equality both in respect to resistance and temperature coefficient. This last adjustment can be made by using a certain resistance of manganin in series or shunt with those thermometers which have too high a coefficient.

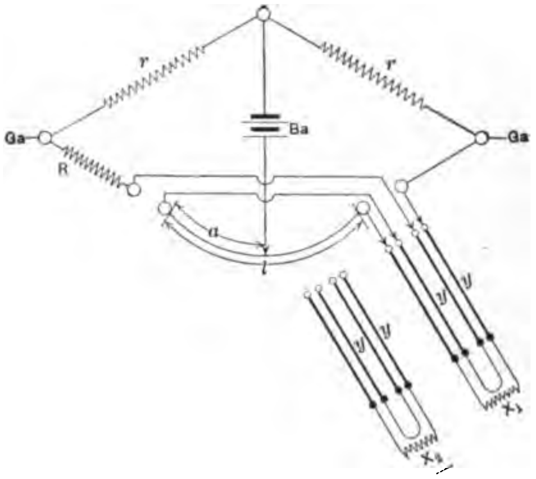

FIG. 7.

The arrangement of connections shown does not entirely compensate for changes in the resistance of the leads. The error, however, would not exceed from this cause 0.1° cent. in an extreme case. The obvious advantage of making the connections in this way is that while nearly complete compensation is obtained, each thermometer has only two lead wires and one common terminal connecting all the thermometers to the galvanometer. The manner of making the bridge connections according to the second method is shown in Fig. 7.

By connecting the bridge in this manner and choosing the ratio arms equal, the leads y, y, entirely eliminate. Thus, the value of the resistance x_1, x_2, etc., is

$$X = R - (l - 2a).$$

This method, while perfectly compensating, requires that two pairs of leads shall be carried to each thermometer. This is a decided disadvantage where many thermometers are to be read at a distance on one bridge. The method recommends itself only where the highest possible precision is required. In this method also the scale may be calibrated in degrees, if desired.

FIG. 8.

The balance point on the wire in either of the above methods may be found with a telephone, but preferably with a galvanometer.

A pointer galvanometer of portable type, such as is used in portable test-sets, is amply sensitive for the purpose.

The illustration, Fig. 8, shows a completed instrument designed on the latter of the above principles for use in measuring the temperature of the soil. The compensating leads shown on the left of the diagram, Fig. 7, are omitted as not being needed for the degree of precision required.

A temperature measurement is made by slightly depressing the handle, which closes the battery circuit, and then rotating it until the galvanometer shows a balance. The position of the pointer then gives on the scale beneath it the temperature in degrees fahr. The same kind of instrument is equally well adapted to reading high temperatures.

One mechanical feature of this instrument deserves mention as being of extreme usefulness. A slide-wire when used as in Figs. 6 and 7, if applied in the customary way, would be very small and delicate in order to have the necessary resistance in the length that is used. This objection is entirely overcome, as follows: a fine silk-insulated manganin wire is wound on a drill-rod of about 2 mm. in diameter, with the turns close together. The drill-rod is slipped out of the winding, and this is laid and shellaced in a groove on the circumference of a circular disk of rubber or wood. The silk insulation is then removed from the exposed surface of the winding by a buffing-wheel. The sliding contact can thus make good contact with the outer surface of the circular helix. This will have about 30 times the resistance of the wire of which it is wound when of the same length as the helix.

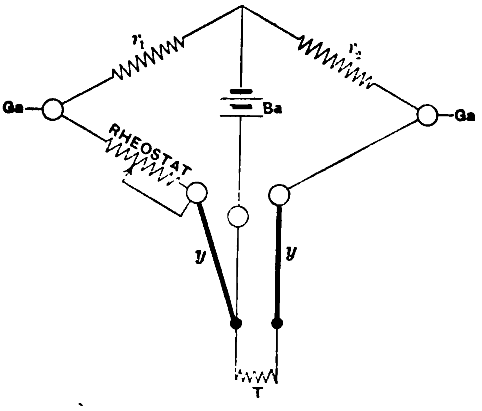

Fig. 9.

This arrangement gives extremely fine variations in resistance, as the slider moves over it and makes a contrivance that is mechanically substantial and not liable to get loose and wear out.

USE OF DIAL OR DECADE WHEATSTONE BRIDGES.

The slide wire bridge directly calibrated in degrees is a very useful and rapid-reading device, but for precision work, combined with robustness of construction, some easily read form of dial or plug wheatstone bridge may be more useful.

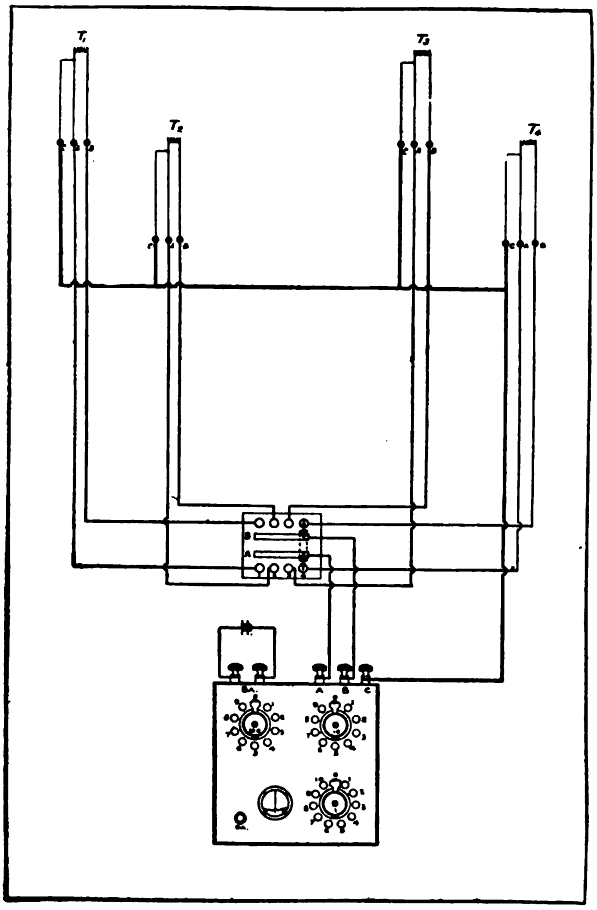

FIG. 10.

When the connections are made as shown in Fig. 9, and the resistances r_1 and r_2 are equal, the leads y y, eliminate. This requires that the total resistance in the rheostat shall equal the resistance of the thermometer, which for this reason, as well as for sensibility, etc., should be high, and that the brush or plug contacts used should be well made, and of negligible resistance. Since no resistance varies with temperature in a strictly linear way, a dial or plug bridge can not be calibrated to read directly in degrees. The studs or plug holes should be numbered decimally, and from the setting obtained for a balance, the temperature is gotten by referring to a curve. Thus, each thermometer in an installation has its own curve, and new thermometers may be added without reference to the old. This method is very convenient for an installation of a large number of thermometers, because of the small number of wires that have to be installed.

Fig. 10 shows four thermometers of a large installation used for measuring the temperature of gases up to 1 200° fahr. in the plant of a large chemical company manufacturing sulphuric acid. Here it was desired that ignorant workmen should take the temperatures without gaining information as to what they were. The dial settings for obtaining a balance were reported to the office, where a clerk looked up the corresponding temperatures on the curves. The thermometers used in these installations were of the form illustrated in Fig. 4.

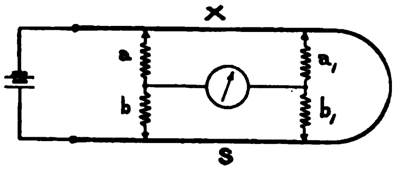

Fig. 11.

Kelvin Double-Bridge Method.

The resistance thermometer as designed for high-temperature work if wound to a suitable resistance is necessarily of considerable size. This unfits it, as compared with thermo-couples, for taking the temperatures of small places or points. Moreover, the thermometers besides requiring considerable skill to construct are costly and more or less fragile. These disadvantages are sought to be overcome by the method now to be described.

As is well known, the bridge connections, due to Lord Kelvin, shown in Fig. 11, is the best arrangement yet devised for measuring a very low resistance. The bridge is balanced when

$$\frac{a}{b} = \frac{a_1}{b_1} = \frac{X}{S}$$

The first two terms being made equal by construction.

$$X = \frac{a}{b} S.$$

With these bridge connections 0.01 ohm can be measured to the same precision as 100 ohms by the ordinary bridge arrangements. By taking advantage of this bridge as a reading device, a high-temperature thermometer can be constructed as shown in Fig. 12.

The small spiral of resistance wire to be measured at the end of the porcelain tube is of No. 20 Haræus platinum. The current and potential leads are of a cheaper grade of platinum. In fact, it is a positive advantage to have the potential leads of an impure platinum, because of its low coefficient, which may be about 0.6 that of pure platinum. The connections as arranged for measuring a number of thermometers would be as shown in Fig. 13.

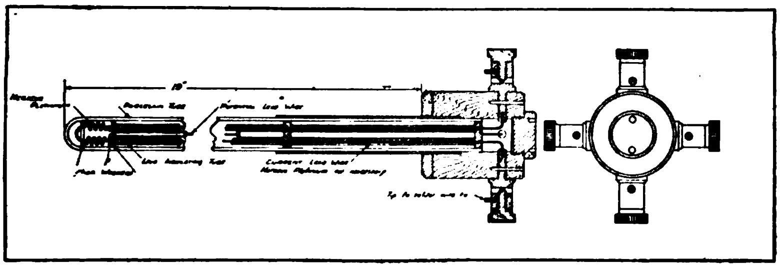

FIG. 12.

To measure a temperature with this arrangement, the terminals p, p^1, are moved by a switch to the potential terminals of the thermometers to be measured, while the thermometers to the right of the one being measured are cut out of circuit by y which keeps the resistance of the "yoke" low, as required by theory. A balance on the galvanometer is obtained by moving the plug N and the slider S. The slide-wire on which S moves would consist of a substantial manganin wire lying over a scale, marked off in degrees centigrade, if it is desired to make the bridge direct-reading. The only uncertain element in the method is the possibility of the ratio $\frac{a}{b}$ and $\frac{a_1}{b_1}$, Fig. 11, becoming variable in an unknown way through a change in the resistance of that portion of the potential leads which lie in the thermometer tube. This uncertainty, however, is practically avoided if the resistance a is made sufficiently high.

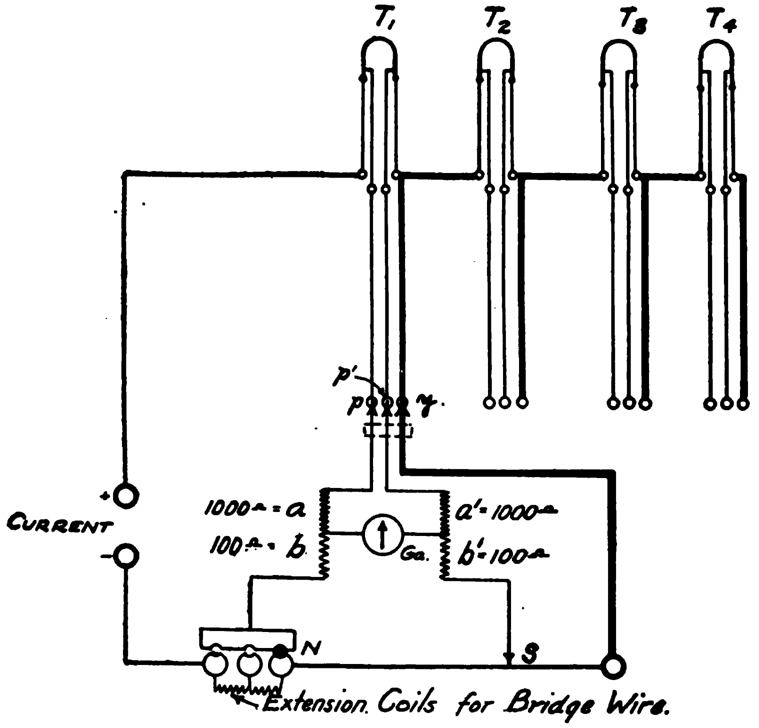

FIG. 13.

Calculation shows that if a is chosen as high as 250 ohms, the maximum error from this cause with a thermometer constructed like that of Fig. 12 will not exceed 0.1° cent. The resistance, a, may, however, be as high as 1 000 or even 5 000 ohms, thus practically reducing the error to zero.

The necessity of having a high resistance in the ratio coils requires that the galvanometer used shall have a greater sensibility than can easily be gotten in a portable pointer instrument. There are, however, available several very convenient forms of semi-portable suspended-coil types of galvanometers, having an attached telescope and scale which are amply sensitive for the purpose.

DIRECT-DEFLECTION METHOD OF READING TEMPERATURES.

Direct-deflection methods of measuring physical quantities, as well as temperatures, depending as they do upon the calibration of a scale, seldom have the precision of zero methods. They possess, however, the advantage of better showing, the variations as they occur in changing quantities, while no manipulative action is required on the part of the observer. For these reasons, largely, all commercial electrical measuring instruments are of the deflection type, though inferior in precision to the null methods used for calibration and other purposes in the laboratory. Recognizing this principle, the writer has designed the instrument to be described, which will read temperatures as readily as a voltmeter reads volts.

THE RATIOMETER.

The instrument can be called a *ratiometer* because it measures by direct deflection the ratio of an unknown to a known quantity, irrespective within wide limits of the operative current used. Thus the ratio measured may be that of an unknown to a known resistance, when the instrument becomes a deflection-ohmmeter, or a capacity-reactance to a resistance, when it can be used as a speedometer, or, as in the present case, a resistance which changes with temperature to a fixed resistance, when it serves as a direct-reading deflection-thermometer.

Since the angle of deflection of a deflection instrument is apparently doubled by using a mirror giving twice the effective sensibility of a pointer instrument otherwise the same, a system using a mirror has been adopted, and utilized in such a manner that the instrument is quite as portable as a voltmeter or ammeter.

Fig. 14 is an illustration of the instrument with its case on, and Fig. 15, of the same shown in section. Fig. 16 gives the diagram of connections of the instrument as used for temperature measurements, and Fig. 17 illustrates details of the deflecting system and the shape of each of the pole pieces.

C_1 and C_2, Fig. 16, are two flat coils mounted on the movable system, a, b, c, Fig. 17, having a damping frame of aluminum.

The two coils have *like* polarity on the same side. The system rotates between two iron crescent-shaped pole pieces of opposite polarity, Fig. 17, *p*. The axis of rotation of the system approximately coincides with the center of the outside circle of the crescent. Hence, when the system rotates, one coil moves so as to get more under the pole faces, and the other coil more from under the pole faces. Now, if currents flow through both coils, and in such a direction as to cause *both* coils to try to move from under the pole faces, the system will seek a position of equilibrium which is independent of the actual value of the currents flowing and which depends only upon the ratio of the portions of the main current, which divides to flow in the two coils. This is true, provided only that the system is under no spring control. The leading-in wires, three in number, are, in fact, made of such delicate strips of silver that they exercise a negligibly small control as compared with the control of the magnetic forces. If, now, the ratio of the currents in the two coils is altered, the system seeks a new position of equilibrium again, independent of the value of the battery current.

FIG. 14.

Referring to the diagram of connections, Fig. 16, *R* being a fixed resistance, and T a resistance which varies with the temperature, the extent of the deflection determines the ratio $\frac{T}{R}$, whatever be the value of the battery current.

Since, also, y is a lead wire on the R side equal to y on the T side, the method nearly compensates for changing resistance in the thermometer leads. The reading device is mostly explained by Fig. 15.

The scale is of translucent celluloid, mounted on the lower part of the front of the case, and may be divided to read in ohms, revolutions per minute, or degrees centigrade. In the telescope the scale is seen brilliantly illuminated by ordinary room light.

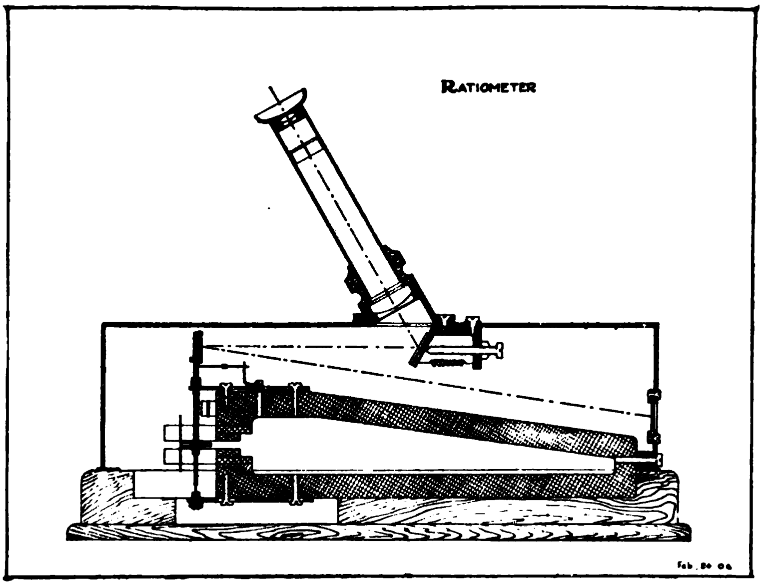

FIG. 15.

The telescope can be removed when the instrument is to be packed in its carrying case. The special shape of the aluminum frame of the system is adopted so as to give good damping, and this makes the instrument nearly dead-beat. The instrument operates for temperature measurements on three or four series connected dry cells, or it may be used with a commutated current from a hand magneto.

To read any temperature, it is only necessary to place the thermometer, joined by a lamp-cord to the instrument, in the place where the temperature is required, and look into the telescope. The scale appears to move under the cross-hair of the eye-piece to the temperature reading.

The ratiometer may be made sensitive to temperature changes of about 0.1° cent., or less, and can be relied upon to be as accurate as the scale is originally calibrated, with the exception of possible fluctuations of 1, or at the most 2 degrees. These irregularities are due to imperfections in the construction, or imperfect balancing of the coil. The error is not progressive, however, and fair reliance can be placed upon its indications. It is especially valuable for rapidly taking the high temperatures of furnaces, and the like. A suitable thermometer to use with this instrument would be one like that illustrated in Fig. 4.

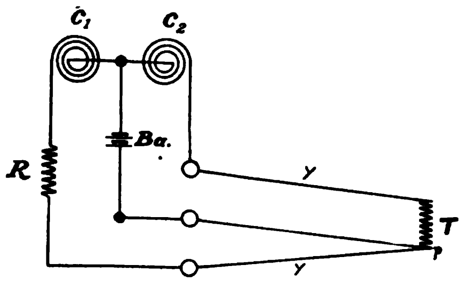

FIG. 16.

DEFLECTION METHODS USING CONSTANT CURRENTS.

It is often required to read and record temperature differences, possibly very small differences, which must be determined with a high percentage accuracy. A thermo-couple is customarily employed for this purpose, placing one junction in the place of higher, and one in the place of lower temperature. Resistance thermometers may, however, be employed to advantage, especially if the temperature difference is small and great precision is required.

The writer has recently been connected with the design, calibration, and use of a temperature-difference recording apparatus which embodied the highest refinements in this kind of measurement, commercially applied. A brief description of this apparatus will best explain the methods to employ, the precautions that should be used to obtain precision, and the results which can be obtained.

The requirement was to obtain a continuous photographic record of the temperature difference between two brine mains carrying brine for refrigeration purposes. The temperature of the brine in one main was about – 38° cent., and in the other, about – 36.5° cent. It was sought to have the error at all times not greater than 0.01° cent. By taking a photographic trace of the temperature difference at each instant, and by obtaining with a planimeter the average height of the ordinates expressing temperature-differences, the average temperature-difference for any period of time could be found. This result was fully obtained.

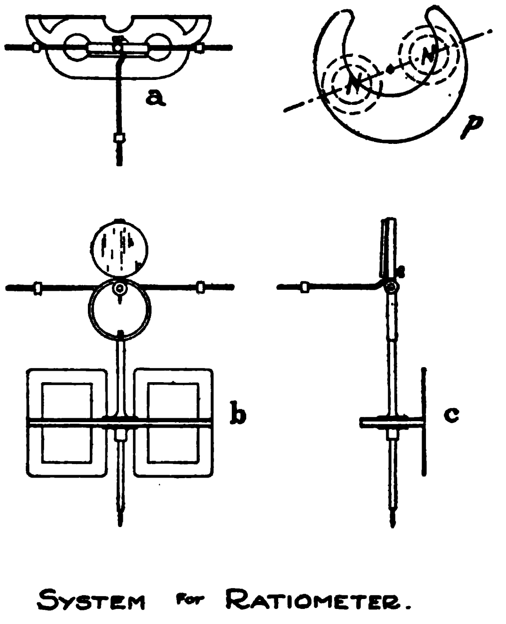

Fig. 17.

An ordinate 500 mm. high corresponded to 5° cent. The deflecting instrument used was a D'Arsonval galvanometer of special construction, having a reflecting system. The record was traced on photographic paper, known to the trade as " rotograph " paper. This paper was wound on a brass cylinder about 55-cm. long and 12.5 cm. in diameter. By means of a clock movement the cylinder made one revolution in 12 hours. Two cylinders were provided, so that an exposed one could be immediately replaced by an unexposed cylinder.

The galvanometer was placed in one end of a box about 1.2-m. long. By suitable optical devices, the spot of light, about 1 mm. in diameter, was reflected from the galvanometer mirror upon the slowly rotating cylinder covered with the sensitive paper. The movements of the spot of light were parallel to the axis of the cylinder, and proportional to the temperature-difference. The source of light was an incandescent lamp. Another optical device cast another spot of light upon a translucent scale, where the deflections could at any time be observed.

Two platinum resistance thermometers, exactly alike, were used, one being placed in each brine main at a distance of several hundred feet from the recorder, being connected with it by lead-covered compensated leads. One of these thermometers is described in connection with Fig. 1 above. Each thermometer with its leads formed an arm of a wheatstone bridge. The two other arms were made of equal manganin resistances, each 200 ohms. When the thermometers were at the same temperature, the bridge was balanced, and the galvanometer deflection read zero; that is, the spot of light fell on the scale at the same point as it would with the circuit open. A fixed mirror made a trace, near the center of the paper, as a reference line from which the extent of the deflections could be measured. When the two thermometers were at a different temperature, the deflections were very nearly proportional to this difference, irrespectively of the mean value of the two temperatures, and to the current entering the bridge. Hence, to maintain the empirical calibration of the scale, it was necessary to provide that the current through the bridge should remain constant to within the percentage precision at which the apparatus was designed to operate. The manner of doing this, as well as the general plan of the method, is best explained by referring to Fig. 18.

The source of current was a battery of eight storage cells. This current could be held constant within a fraction of one per cent. by varying the rheostat resistance in the battery circuit. The current was known to have the standard value when the galvanometer, *G*, in the standard-cell circuit shown gave no deflection. It was found in practice that the rheostat resistance had to be changed only a few times in a day, and then only by small amounts. Since the scale was calibrated so that 1 mm. was equal to 0.01° cent., the galvanometer had to be fairly sensitive. Only 90 ohms, *R* in the diagram, could be used in its circuit. The galvanometer coil had 333 ohms of copper wire winding, and since copper changes about four-tenths per cent. in resistance per degree centigrade, it was necessary to avoid changes in the galvanometer sensibility due to room temperature changes. The temperature of the box enclosing the galvanometer was, therefore, held constant

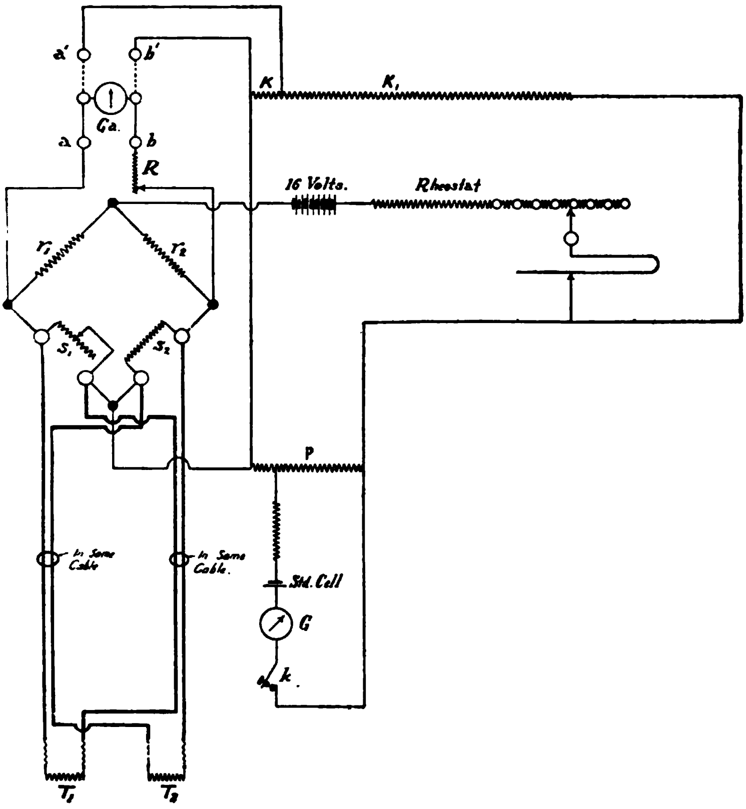

Fig. 18.

within about one-half degree by means of an electric thermostat.

Since it is impossible to adjust two resistance-thermometers to exact equality, when at low temperatures, the difficulty was avoided by shunting each thermometer, one with 10 000 ohms, and the other with a resistance near 10 000 ohms, which thus made both thermometers act in balancing the bridge as if they were exactly equal when at the same temperature.

In calibrating the apparatus, a necessary adjustment was made by placing both thermometers in a tank containing well-stirred brine at about – 35° cent., and then varying one of the shunts, S_1 and S_2, until the galvanometer showed no deflection. Another adjustment was made by placing one thermometer in one brine tank, and the other in another brine tank. The temperature-difference between these brine tanks could be controlled, and this difference was accurately measured by taking a great many readings with specially constructed mercury thermometers with Reichenstalt certificates. The corresponding galvanometer deflections being noted, the scale became calibrated. By adjusting the resistance, R, in the galvanometer circuit, the value of the scale could be varied as desired.

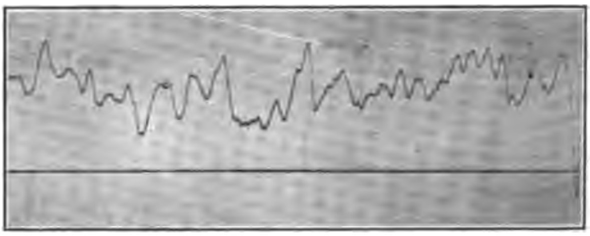

FIG. 19.

The calibration thus briefly outlined was worked on for about three weeks, many refinements not mentioned here were used, hundreds of readings were recorded, and many checks made upon the observations taken. It was demonstrated, as a net result, that this apparatus and method gave continuous temperature-difference records that were not in error over 0.01° cent., the mean temperature measured being about – 37° cent., and the average difference, about 1.5° cent. In Fig. 19

is given on a much reduced scale one of the record curves obtained in a run of 12 hours.

THERMOELECTRIC PYROMETRY.

This paper would be incomplete without some mention of methods of measuring temperatures by means of thermocouples. The subject, however, is extensive, and those interested are again referred to " High Temperature Measurements," by Le Chatelier, where it is very fully treated in Chapter VI. On page 132 of this work it is stated:

> The thermoelectric method possesses very considerable advantages for use in the laboratory, as well as industrially, such as smallness of the thermoelectric substance, rapidity of indications, possibility of placing at any distance the measuring apparatus.

The author adds, page 144:

> In many industrial operations it is desirable to know a temperature in the range of 400°C. to 1500° C. to 10°. This accuracy can be obtained with industrial forms of the thermo electric pyrometer, but only when certain conditions are fulfilled by the maker and user.

These statements cover the generally accepted views regarding the advantages to be obtained in using thermo-couples, but from what has been shown respecting the forms and uses of resistance thermometers, all the advantages stated for thermocouples are equally to be obtained with resistance thermometers. where the upper temperature limit of the latter is not exceeded. Possibly, thermo-couples can be used with somewhat higher temperatures, but the gain is probably not great if the Kelvin bridge method be used with a properly constructed potential-point thermometer.

Thermo-couples for high temperature work are best made of a combination of platinum and platinum with 10% rhodium. This combination is recorded as giving:

565	microvolts	between	0°	and	100°	cent.
3 450	"	"	0°	"	448°	"
8 500	"	"	0°	"	930°	"
15 100	"	"	0	"	1 500°	"

The electromotive force developed as a function of the temperature may be measured most accurately with a potentiometer, and most conveniently by the indirect method of noting the current through a constant or nearly constant resistance circuit with a galvanometer. Such a galvanometer needs to have greater sensibility than can easily be obtained with a portable pivoted instrument.

Suspended-coil instruments, of the so-called marine type, which require no special leveling, serve the purpose well. They can be supplied with the telescope and scale attached to the galvanometer, and thereby become semi-portable.

For high temperature work, the thermo-couple must be protected in porcelain tubes, in a manner similar to resistance thermometers.

THE MEASUREMENT OF EXTREMELY HIGH TEMPERATURES.

Many scientific investigations and industrial operations now require that temperatures shall be measured at which all materials deteriorate or become fused or destroyed. The electrical methods directly applied must fail to be of service here, and one must resort to radiation pyrometry. The various methods proposed for measuring high temperatures by means of the radiation given off from a hot body have recently received much study, and very successful developments have followed along this line. The subject, however, does not fall within the scope of this paper, and reference must be made to the above mentioned treatise of Le Chatelier, and to an excellent summary of this and other subjects relating to high-temperature measurements by Dr. C. W. Waidner.[1]

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[1] " Methods of Pyrometry." Reprinted from the Proceedings of the Engineers' Society of Western Pennsylvania, September, 1904.

DISCUSSION ON "MEASUREMENT OF TEMPERATURE BY ELECTRICAL MEANS," AT MILWAUKEE, WIS., MAY 30, 1906.

F. F. Schuetz: I must take exception to several of the statements regarding the thermoelectric pyrometer. The author says:

> All the advantages stated for thermoelectric couples are equally to be obtained with resistance thermometers.

Some of the "not-stated" advantages of some thermoelectric pyrometers, and advantages not possessed by resistance pyrometers, are as follows:

1. Direct readings with wall or portable, pivot, dead-beat indicating instruments whose scales are directly visible.
2. Direct recording of temperatures with a recording device similar to a recording voltmeter or ammeter. A smoked vibrating chart is preferably used as the record-sheet.
3. Use of different range scales upon the same instrument.
4. The use of comparatively inexpensive elements of substantial size, readily insulated and protected; these may in many cases be left bare, and without any appreciable lag in assuming thermal equilibrium.
5. The instantaneous indication of temperatures and variations thereof of molten baths, and metallic plates, etc.
6. Non-fragile couples, and the convenient and cheap replacing of the destructible parts.
7. A pyrometer which may be entrusted to workmen of even less than ordinary intelligence.
8. The comparative inexpensiveness, when not making use of platinum-rhodium couples which are only necessary for temperature above 2600° fahr. (although in some instance temperatures even as high as 2900° fahr. may be measured with the cheaper couples).
9. The practically unlimited length of the couple itself; and the practical possibility of being able to use a great number of these couples and at various points, because of their comparative inexpensiveness.

There is yet another statement which needs correcting, namely:

> Such a galvanometer needs to have greater sensibility than can be easily obtained with a portable pivoted instrument, etc.

The use of a galvanometer is not at all necessary, unless working with the Le Chatelier high-resistance system with the standard platinum-rhodium elements.

A low-resistance system, using cheaper elements which give some five times the electromotive force of the standard Le Chatelier couple, has recently been devised by Professor William H. Bristol of the Stevens Institute of Technology. In this system a wall or portable, Weston, pivot, dead-beat instrument is employed, requiring no particular care in handling.

A paper on this subject was recently read by Professor Bristol at the Chattanooga Meeting of the American Society of Mechanical Engineers.

It is admitted that for extremely refined and accurate work the thermoelectric pyrometer must give place to the resistance pyrometer; but for ordinary commercial, industrial, and testing purposes, where indications to within one or two degrees are satisfactory, it is thought that the thermo electric pyrometer is and will continue, because of the advantages enumerated, to be the most desirable and satisfactory temperature-measuring device for temperatures up to 2900° fahr., 1600° cent.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

INTERURBAN TEST-CAR OF THE UNIVERSITY OF ILLINOIS.

BY THOMAS M. GARDNER.

About 15 years ago the first serious consideration was given to railway testing work by an educational institution when one of the universities of the middle West* installed a locomotive-testing plant. Shortly after, the University of Illinois obtained its dynamometer car, which was in service for some years and was later replaced by a second car having many improvements over the original one. This car is now operated jointly with the Illinois Central Railroad. It was used at the time of making the recent exhaustive investigations for the electrification of the New York Central Railroad. The knowledge acquired from the above mentioned sources has been of much value both commercially and educationally.

It is a recognized fact that on account of the rapid growth of street and interurban railways, and the electrification of steam roads, there should be electric cars properly equipped for investigation along these lines. Numerous tests have been made of electric locomotives and of street cars temporarily fitted up with instruments. Perhaps the best known of these are the tests conducted some 18 months ago on one of the electric roads in Indiana.

The university authorities seeing the value of the dynamometer car to the department of mechanical engineering, and realizing what a promising field was opened in electric railway work, added to the equipment of the electrical engineering department an interurban car for testing purposes. So far as the writer knows this is the first car of its kind owned by an educational institution.

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*Purdue University.

The object of laboratory work is to make clearer to the student many facts mentioned in the class-room, as well as to help him to become familiar with the construction, operation, and use of the different machines; so it is believed that this car will materially supplement the recitations and lectures in the street railway course.

In this section of the middle West interurban track construction is going on at a rapid rate, and in the next few years the mileage of electric railways will be greatly increased. The car at present can run only between Champaign and Danville, Illinois, a distance of 35 miles, but in a few months, when the connection with the St. Louis line is completed, it will be able to travel over practically all of the Illinois Traction System. Thus, those taking this work will be given an opportunity to study the general requirements of electric railroading, meeting the different employees and learning something of the various conditions of operation; so being able more thoroughly to understand the requirements of practice. It is the intention of the department to coöperate with the management of the companies whenever possible, endeavoring to solve some of the problems of mutual interest that are constantly occurring. Different pieces of apparatus can be tested, and their strong as well as their weak points, both mechanical and electrical, can be noted.

Many engineering students are taking up electric traction, and it is hoped that when this car is completely equipped, and the course fully rounded out, that those graduating will be much better fitted for this kind of work than formerly.

Most of the time during the present year has been given to the building and installing of the different measuring instruments, rather than to the acquisition of scientific data.* Several of the theses of the present senior class have been upon the design and construction of special apparatus for the car, while some of the other theses have depended upon such tests as it has been possible to make.

The car as shown in Fig. 1 was received from the manufacturers last fall. It is of the high-speed interurban type, weighing as equipped approximately 27.5 tons. The general dimensions of the car body are as follows: length over corner-posts 34 ft. 4 in.; length over vestibules 45 ft.; width over all, 8 ft. 4 in.; The interior is divided by a partition into two compartments, one

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*Numerous changes in instrument equipment are in contemplation.

being 11 ft. 10 in., and the other 22 ft. 6 in. in length. The larger of these may be called the computing room, and it contains a typewriter desk, sectional bookcases, filing cabinet, and chairs. The smaller one is quite filled with car-control apparatus and the table of testing instruments. The enclosed vestibules are fitted with the usual fold-doors. The interior finish is of golden oak, while the exterior is painted dark blue, with orange trimmings, the university colors.

The trucks are of standard construction; one set of wheels is of rolled steel and the other of cast iron, both having Master Car Builders' treads and flanges. The wheel-bases are 6 ft. 4 in., and the distance between center-bearings is 22 ft. 4 in.

Fig. 1.

The motive power equipment has four motors rated at 40 h.p. each, with a pressure on the trolley wire of 500 volts. The gear-ratio is 22-62, which gives a car velocity of approximately 45 miles per hour, with 1 300 rev. per min. of the armatures. Much of the apparatus which would otherwise be placed under the floor of the car is shown in Figs. 2 and 3.

In Fig. 2, on the right is seen the switch-group and circuit-breaker; the limit-switch and the line relay are placed just behind the door and so do not show in the picture. In this same room are also the battery-charging relay and double-throw switch for that purpose. To the left of the door is to be seen the testing table with numerous pieces of apparatus mounted upon and placed beneath it. Although considerable space is taken by this plan, yet for inspection and instructional purposes it was deemed best to have them arranged as shown. Whenever desired, the metal covers of the car-control apparatus can be removed and the students can thus see the mechanical operation. Fig. 3 is a view taken from the opposite end of this same compartment.

Fig. 2.

In the adjacent vestibule is mounted a large cut-out switch, and an integrating wattmeter for recording the electrical energy supplied to the car-lighting circuit, and to the motor which drives the air-compressor. In addition to these are the master-controller, motorman's air-brake valve, air-pressure gauge, hand-brake, and sand-box. In the other vestibule, besides the usual equipment, has been placed the governor for the air-pump.

The rest of the control apparatus, the reservoirs for the air-brake, and the air-compressor, are in their usual positions. The brake system is operated directly by compressed air.

Instrument Wiring. Inserted in the main circuit is a large integrating wattmeter, reading total energy supplied to the car. A branch circuit supplies the electric energy to the air-compressor. The main current passes through a graphic recording ammeter and a standard shunt, which in connection with a millivoltmeter may at intervals be used as a check. An ammeter is inserted in the exciting circuit of this same recording ammeter, to read the necessary exciting current. Alongside is a short-circuiting switch for cutting out the large ammeter. Adjacent to this instrument is a recording voltmeter, which is likewise supplied with a low-reading ammeter, for measuring its exciting current. On this table are also four switches, to which the leads from the individual motors are connected for the purpose of control-

FIG. 3.

ling the separate motor currents. A small plug-board is conveniently placed for voltmeter use, from which run pressure wires to the several armatures and fields, so that the drop in voltage across them may be obtained. Nearby are electric instruments for indicating car velocities and accelerations.

In Fig. 2 is shown an integrating wattmeter mounted on the end partition, near the roof, and in Fig. 3 to the left of the door is to be seen an autometer, which gives the velocity of the car in miles per hour, miles per trip, and total mileage. Above the testing table is the time-marker clock, which controls the time-needles of the recording instruments, intervals of five seconds being indicated by side marks on the records.

FIG. 4.

Apparatus for Determining Speeds and Accelerations. Fastened to the frame of the truck as shown in the accompanying photograph, Fig. 4, is placed a direct-current low-voltage generator of 0.5-kw. output. This is driven by means of two sprockets and a chain; one of the gears being around an axle, the other being keyed to the armature shaft. On the opposite end of this shaft is a gear which drives a series of wheels, to the last of which is affixed a flexible shaft, which extends up through the car floor and drives the autometer just mentioned. As it is desirable to determine not only the velocities but also the accelerations, and since all of the different forms of mechanical accelerometers take into account not only the acceleration but the inclination of the car, it was decided that only apparatus that would give the former should be used.

Advantage was taken of the principle, that as acceleration is the rate of change of velocity, and since the induced electromotive force in the secondary of a transformer is directly proportional to the rate of change of current in the primary, and as the generator supplied current according to its speed, therefore the voltage induced in the secondary would be directly proportional to the rate of charge of velocity of the car. Hence the voltmeter could be made to read directly the acceleration in miles per hour per second, or feet per second per second, and show whether the values were negative or positive.

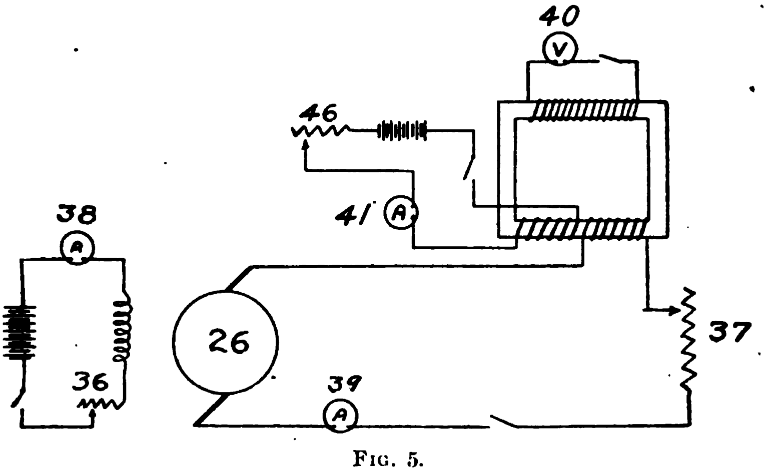

Fig. 5.

The generator is so designed that its current varies directly with the revolutions per minute of the armature, its curve of regulation being a straight line, between the working limits. The maximum current taken is 10 amperes. Fig. 5 is a diagram of this apparatus. The field of the generator is separately excited by means of a storage-battery. The reading of the ammeter inserted in the circuit is maintained constant by the means of resistance, 36. From the armature of the generator, 26, runs a wire to one of the terminals of a secondary coil of a 0.5-kw. transformer, the turns in the winding of which are such as to reduce the pressure from 2 200 volts down to 220 or 110, as desired in lighting work. This direct current passes through

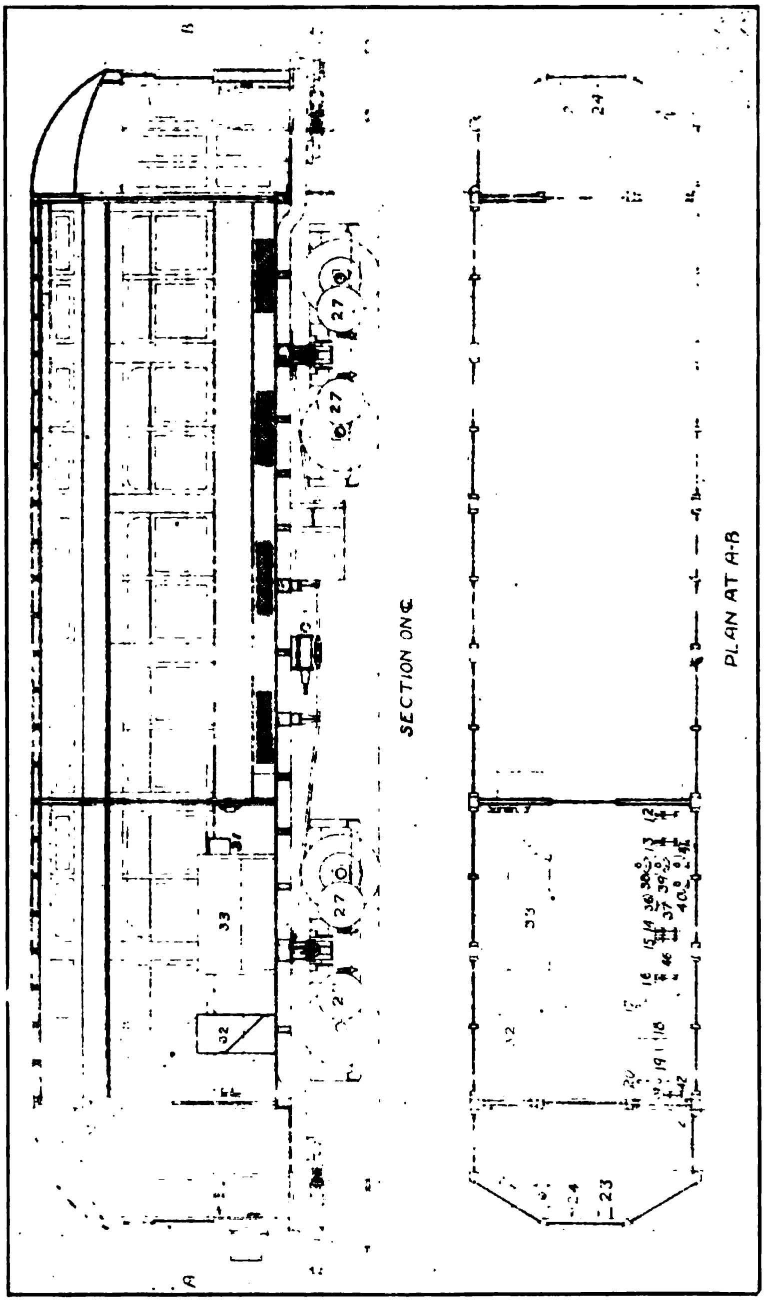
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FIG. 7. FIG. 8.

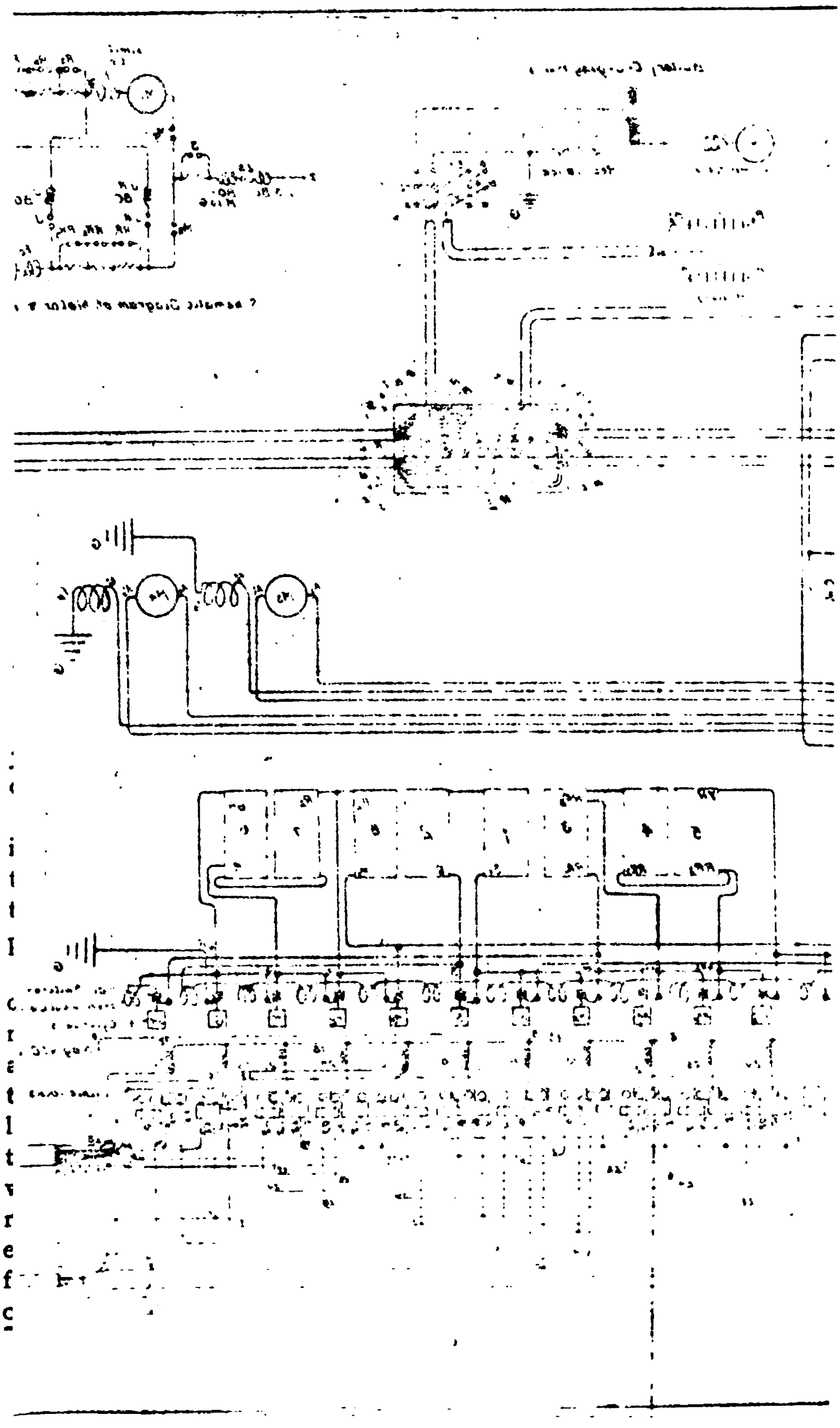
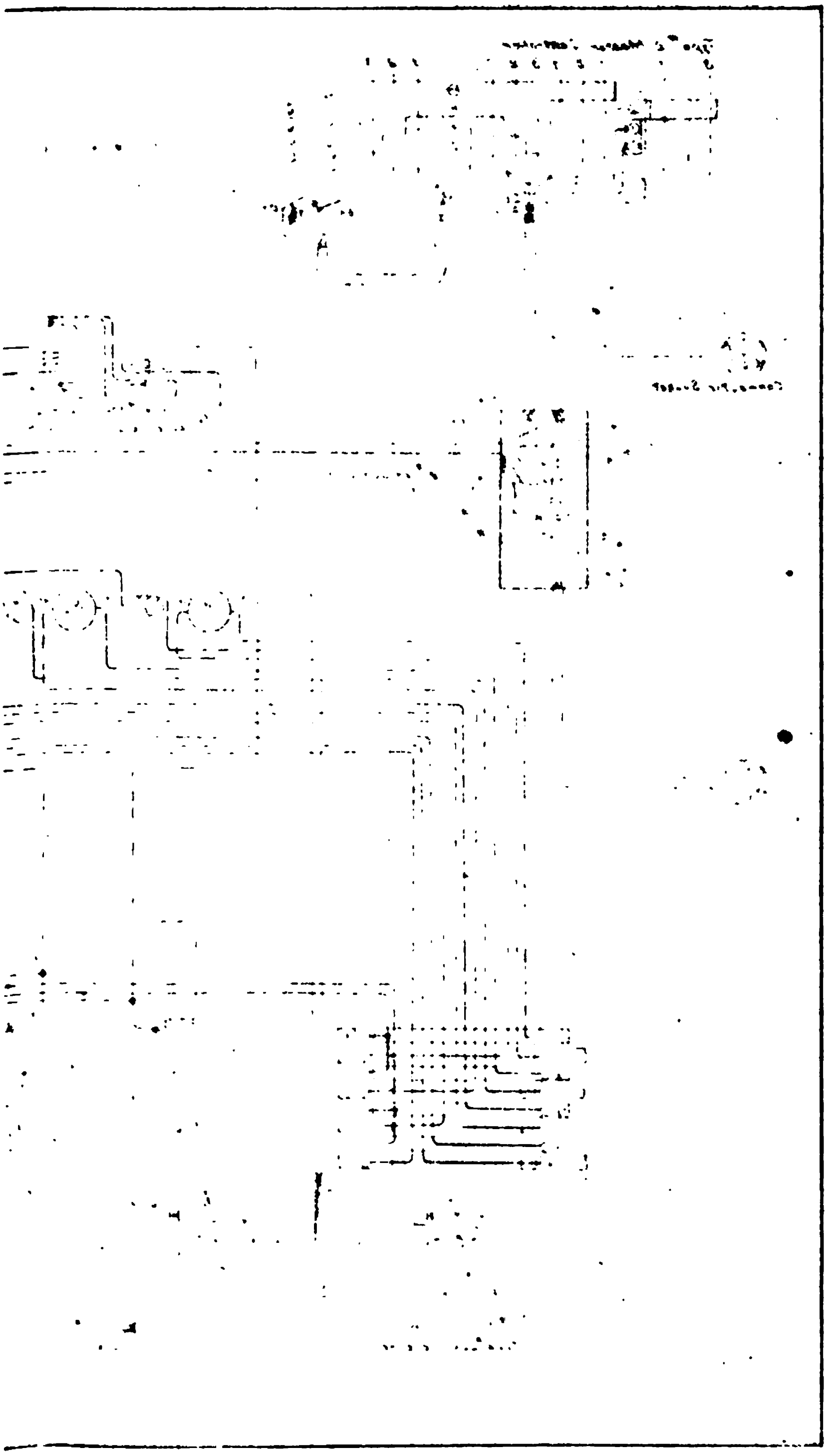


Fig. 6.


Type "C" Master Controller
Connecting Socket

the rheostat, 37; switch and ammeter, 39; back to the generator. From this ammeter the velocities of the car may be read. In the high-voltage or primary coils of this transformer is a voltmeter, which gives the electric pressure proportional to the rate of change of current in the secondary, now used as a primary. This reading is directly proportional to the acceleration as before mentioned. This voltmeter must have its zero at the middle of its scale, because the needle must swing in one direction or the other, as the acceleration is negative or positive. When the speed is constant it is evident that the reading must be zero.

It was found that the values of acceleration at low speeds were not satisfactory, because of the small amount of current in the generator circuit giving too low a magnetic density in the iron core. The other secondary coil was then separately excited* by means of a battery of storage cells, and no further trouble has resulted.

The current is kept at a constant reading in the ammeter, 41, by means of resistance, 46. This apparatus gives extremely accurate values of velocity and acceleration, and is a modification of that described by Professor Owens of McGill University.

Instead of indicating ammeter and voltmeter for the readings just mentioned, will soon be placed instruments of the recording type, so that continuous records may be taken.

In a short time there will be added a graphic curve recorder, indicating the curvature of the track; an inclinometer showing the variation in the grade; and diaphragms suitably placed on the sides and ends of the car for obtaining the various wind pressures.

Fig. 6 is a general wiring diagram of this type of car. It has only been slightly modified by the insertion of switches in the motor leads, the running of pressure wires to the fields and armatures from the small plug-board in testing room, and by the insertion of the instruments in several of the circuits. The location of much of the apparatus so as to be accessible when the car is in motion has compelled the running of many of the wires along the sides, or under the extra floor in the testing room, which has been put down in sections so that it may easily be removed. Access to the transite lined conduits thus formed between it and the car floor proper, may be quickly obtained.

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*Thesis of Saathoff and Wooster.

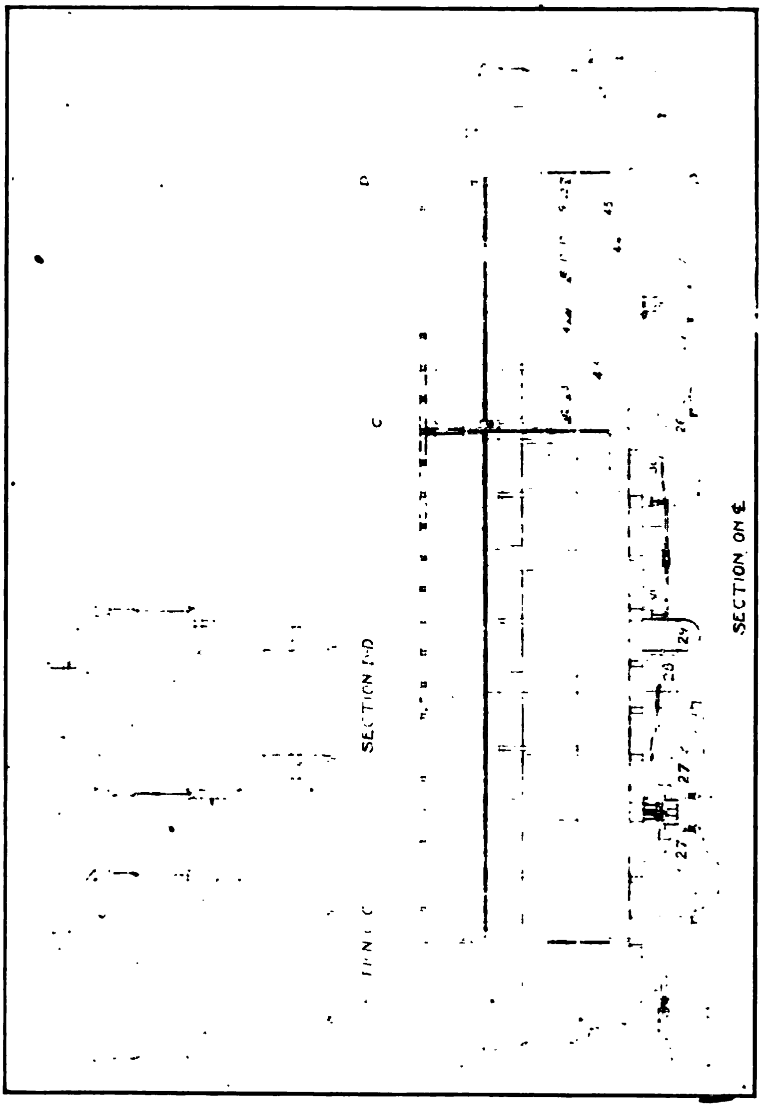


Fig. 9. Fig. 10. Fig. 11.

The car in plan and in longitudinal and cross-sectional elevations is seen in Figs. 7, 8, 9, 10, and 11. Many of the different pieces of apparatus for car control, and for measurement, have been numbered to give a more complete idea of their arrangement.

1 and 2, Switches for charging equipment batteries.
3, Switch for charging instrument battery.
4, Battery-charging relay.
5, Autometer.
6, Time-marker clock.
7, Integrating wattmeter for total load.
8, Limit-switch.
9, Line relay.
12, 13, 14, and 16, Individual motor switches.
17, Ammeter for exciting current to recording voltmeter, 18.
19, Recording ammeter.
20, Exciting current ammeter for 19.
21, Recording ammeter short-circuiting switch.
22, Main switch.
23, Master-controller.
24, Motorman's air-valves.
25, Sand-boxes.
26, Generator for speed-recorder.
27, Motors.
28, Storage-batteries for switch-group.
29, Main air-reservoir.
30, Resistances.
31, Motor control cut-out.
32, Circuit-breaker.
33, Switch-group.
34, Millivoltmeter used in connection with the standard shunt, 42.
35, Wattmeter measuring energy supplied to the air-compressor.
36, 37, and 46, Resistances used in connection with speed-recorder and accelerometer.
38, 39, 40, 41, Ammeters and voltmeters of above apparatus.
42, Standard shunt.
43, Reverse switch.
44, 0.5-kw. transformer.
45, Storage cells.

DISCUSSION ON " THE EDUCATIONAL VALUE OF AN ELECTRIC TEST CAR" AT MILWAUKEE, WIS., MAY 30, 1906.

P. M. Lincoln: What degree of accuracy can be obtained from the accelerometer? The accelerometer, as I understand it, operates from a change of voltage in the transformer, which is caused by a change in current, which in turn is caused by a change in speed. It seems to me that the magnetic lag of the transformer would cause a considerable error in regard to the change in voltage and change in current. Just how much that amounts to, and how an accurate result could be obtained is the question.

D. C. Jackson: I would like to call attention to several advantages of this kind of apparatus. The title of the paper is " The Educational Value of an Electric Test-Car." Now, from the standpoint of instruction, I do not believe such a test-car brings returns worthy of the great amount of money that goes into it. On the other hand, there are two features of pronounced advantage. One lies in the fact that the college can construct, maintain, and operate such apparatus very advantageously, because, for one thing, it is a natural holder of such apparatus The work of investigation can be done by the colleges with such apparatus, and the results will be made public so as to be useful to all concerned when the work is completed. The results of similar investigations might not be made public by private corporations owning such test apparatus. The second advantage is that it brings the colleges into intimate contact with operating managers and engineers, and there is no question about the educational value to both the colleges and the corporations that come from that feature. From that standpoint I think the title of the paper is justified.

M. K. Akers: As to the accelerometer, I am sorry I cannot give any precise answer to the question; but the transformer, being excited by the direct current from the machine, and there being but a comparatively slight change in the current, I think the hysteresis would introduce but slight error and have a limited effect.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

THE ART OF INVENTING.

BY EDWIN J. PRINDLE.

There are many kinds of invention. The poet, the artist, the playwright, the novelist all exercise or may exercise invention in the production of their works. The merchant may exercise invention in the devising of a new method of selling goods. The department store was an invention of this class.

The subject of my paper is, however, the art of making technical inventions, and particularly patentable inventions. And, first, of its commercial importance; for the engineer is concerned with things having a commercial value. By the art of inventing, wealth is created absolutely out of ideas alone. It usually takes capital to develop an invention and make it productive, but not always. A notable recent example is Professor Pupin's loaded telephone line. He received a very large sum of money, and his expenditures, as I understand, were comparatively trivial.

The certificate of ownership of an invention is a patent, and the importance of the art of invention will be made apparent from a brief consideration of what rights a patent confers and of the part that patents play in the industries.

A patent is the most perfect form of monopoly recognized by the law. As was said in a recent decision:

> "Within his domain, the patentee is czar. The people must take the invention on the terms he dictates or let it alone for seventeen years. This is a necessity from the nature of the grant. Cries of restraint of trade and impairment of the freedom of sales are unavailing, because for the promotion of the useful arts the constitution and statutes authorize this very monopoly."

There is an enormous amount of wealth in this country that is based upon patents. As an instance, might be mentioned the fact that the United Shoe Machinery Company is, by means of patents, able to control the sewing machines upon which ninety per cent. of the welt shoes in the United States are sewed. The Bell Telephone Company, and the Westinghouse Air Brake Company and many other corporations of the first importance built themselves up on patents. Patents have become so well recognized a factor in commerce that, in many lines of manufacture, concerns do not depend simply upon cheapness of manufacture, or quality of product, to maintain their trade, but they count on always having a product which is at least slightly better than that of their competitors, and which is covered by patents, so that they do not have to compete with an article of equal merit. And they keep a corps of inventors at work in a constant effort to improve the product, so that, when the patents now giving protection have expired, they will have a better article to offer, which shall also be protected by patents.

Inventing has become almost a recognized profession. Many large concerns constantly employ a large corps of inventors, at liberal salaries. Besides the inventors employed by large corporations, there are many inventors who have maintained their independence, and are free lances, so to speak. Some inventors have become wealthy almost solely by their inventions, such as Edison, Bell, Westinghouse, Marconi, Pupin, Tesla, and Sprague. A considerable number of the smaller manufacturing concerns are built largely or wholly upon the inventions of their principal owners.

Aside from the question of financial returns from inventing, the inventor has the satisfaction of knowing that he is a producer of the most fundamental kind. All material progress has involved the production of inventions. Inventors are universally conceded to be among the greatest benefactors of the human race.

The art of invention is therefore one of great commercial and economical importance, and it becomes a matter of much interest to know how inventions are produced. It is my object to attempt an explanation of the manner of their production.

If it be inquired on what grounds I offer an explanation of this apparently most difficult subject, I reply that, in the practice of patent law, I have often had occasion and opportunity to inquire into the mental processes of inventors, and that the subject is one to which I have given considerable attention.

It seems to be popularly believed that the inventor must be born to his work, and that such people are born only occasionally. This is true, to a certain extent, but I am convinced there are many people who, without suspecting it, have latent inventive abilities, which could be put to work if they only knew how to go about it. The large percentage of inventors in this country compared with all other countries, shows that the inventive faculty is one which can be cultivated to some extent. The difference in ingenuity is not wholly a matter of race, for substantially the same blood exists in some other countries, but it is the encouragement of our patent laws that has stimulated the cultivation of this faculty.

The popular idea seems to be that an invention is produced by its inventor at a single effort of the imagination and complete, as Minerva sprang full grown and fully armed from the mind of Jove.

It is, undoubtedly, true that every inventor must have some imagination or creative faculty, but, as I shall seek to show, this faculty may be greatly assisted by method. While reasoning does not constitute the whole of an inventive act, it can, so to speak, clear the way and render the inventive act easier of accomplishment.

Invention has been defined as " In the nature of a guess; the mind leaps across a logical chasm. Instead of working out a conclusion, it imagines it." The courts have repeatedly held that that which could be produced *purely* by the process of reasoning or inference, on the part of one ordinarily skilled in the art is not patentable, but that the imaginative or creative faculty must somewhere be used in the process. The mind must somewhere leap from the known to the unknown by means of the imagination, and not by mere inference in making the invention. But the inventor, consciously or unconsciously, by proper method, reduces the length of this leap to much more moderate proportions than is popularly supposed.

That reasoning and research frequently enter very largely into the inventive act in aid of the creative faculty is the opinion of Dr. Trowbridge, of Columbia University who said:

" Important inventions leading to widespread improvements in the arts or to new industries do not come by chance, or as sudden inspira-

> tion, but are in almost every instance the result of long and exhaustive researches by men whose thorough familiarity with their subjects enables them to see clearly the way to improvements. Almost all important and successful inventions which have found their way into general use and acceptance have been the products of well-balanced and thoughtful minds, capable of patient laborious investigation."

Judge Drummond, in a decision many years ago, said:

> " Most inventions are the result of experiment, trial, and effort, and few of them are worked out by mere will."

Most inventions are an evolution from some previously invented form. It has been said:

> " We know exactly how the human mind works. The unknown—or unknowable—it always conceives in terms of the known."

Even the imagination conceives in terms of what is already known; that is, the product of the imagination is a transformation of material already possessed. Imagination is the association in new relations of ideas already possessed by the mind. It is impossible to imagine that, the elements of which are not already known to us. We cannot conceive of a color which does not consist of a blending of one or more colors with which we are already familiar. This evolution of an invention is more or less logical, and is often worked out by logical processes to such an extent that the steps or efforts of imagination are greatly reduced as compared with the effort of producing the invention solely by the imagination.

Edison is quoted as having said that " any man can become an inventor if he has imagination and pertinacity," that " invention is not so much inspiration as perspiration."

There are four classes of protectable inventions. These are

Arts,
Machines,
Manufactures, and
Compositions of matter.

In popular language an art may be said to be any process or series of steps or operations for accomplishing a physical or chemical result. Examples are, the art of telephoning by causing undulations of the electric current corresponding to the sound waves of the spoken voice. The art of casting car wheels, which consists in directing the metal into the mold in a stream running tangentially instead of radially, so that the metal in the mold is given a rotary movement, and the heavy, sound metal flows out to the rim of the wheel, while the light and defective metal is displaced toward the centre, where it is not subjected to wear.

The term machine hardly needs any explanation. It may be said to be an assemblage of two or more mechanical elements, having a law of action of its own.

A manufacture is anything made by the hand of man, which is neither a machine nor a composition of matter; such as, a chisel, a match, or a pencil.

The term composition of matter covers all combinations of two or more substances, whether by mechanical mixture or chemical union, and whether they be gases, fluids, powders or solids; such as, a new cement or paint.

These definitions are not legally exact, but serve to illustrate the meaning.

In the making of all inventions which do not consist in the discovery of the adaptability of some means to an end not intentionally being sought after, the first step is the selection of a problem. The inventor should first make certain that the problem is based upon a real need. Much time and money is sometimes spent in an effort to invent something that is not really needed. What already exists is good enough or is so good that no additional cost or complication would justify anything better. The new invention might be objectionable because it would involve counter disadvantages more important than its own advantages, so that a really desirable object is the first thing to be sure of.

Having selected a problem, the next step should be a thorough analysis of the old situation, getting at the reasons for the faults which exist, and in fact discovering the presence of faults which are not obvious to others, because of the tendency to believe that whatever is, is right.

Then the qualities of the material, and the laws of action under which one must operate should be exhaustively considered. It should be considered whether these laws are really or only apparently inflexible. It should be carefully considered whether further improvement is possible in the same direction, and such consideration will often suggest the direction in which further improvement must go, if a change of direction is necessary. Sometimes the only possible improvement is in an opposite direction. A glance at the accounts of how James Watt invented the condensing steam-engine will show what a large part profound study of the old engine and of the laws of steam played in his invention, and how strongly they suggested the directions of the solutions of his difficulties.

We now come to the constructive part of inventing, in order to illustrate which, I will seek to explain how several inventions were, or could have been, produced.

The way in which the first automatic steam engine was produced was undoubtedly this—and it shows how comparatively easily a really great invention may sometimes be made. It was the duty of Humphrey Potter, a *boy*, to turn a stop-cock to let the steam into the cylinder and one to let in water to condense it at certain periods of each stroke of the engine, and if this were not done at the right time, the engine would stop. He noticed that these movements of the stop-cock handles took place in unison with the movements of certain portions of the beam of the engine. He simply connected the valve handles with the proper portions of the beam by strings, and the engine became automatic—a most eventful result.

As one example of the evolution of an invention, I will take an instrument for measuring and recording a period of time, known as the calculograph, because it lends itself with facility, to an explanation from a platform and because my duties as a lawyer have necessitated my becoming very familiar with the invention, and have caused me to consider how it was probably produced.

And first the problem: There was much occasion to determine and record the values of periods of elapsed time; such as, the length of time of a telephone conversation; as the revenue of the telephone companies depended upon the accuracy of the determination. All the previous methods involved the recording in hours and minutes the times of day marking the initial and the final limits of the period to be measured, and then the subtraction of the one time of day from the other. This subtraction was found to be very unreliable as well as expensive. The problem then was to devise some way by which the value of the period could be arrived at directly and without subtraction and also by which such value could be mechanically recorded.

The prior machine from which the calculograph was evolved is the time-stamp, a printing machine having a stationary die like a clock dial and having a rotating die like the hand of the clock, as in Fig. 1. The small triangle outside the dial is the hour hand, it being placed outside the dial because it is necessary that the two hands shall be at the level of the face of the dial and yet be able to pass each other. The hour hand may be disregarded here, as the records needed are almost never an hour long. The manner of using the time stamp to determine the value of an interval was to stamp the time of day at the beginning of the period, and then to stamp the time of day at the close of the period at another place on the paper, as shown in Fig. 2, and finally mentally to subtract the one time of day from the other to get the value of the period.

The inventor of the new machine conceived the idea that, if the time-stamp were provided with guides or gauges so that the card could be placed both times in the same position, and the two records of the time stamp thus be superimposed concentrically (as illustrated in Fig. 3), the value of the period would be represented by the arc marked off by the initial and final imprints of the minute hand, so that, instead of subtracting one record from another, he had only to find the value of the arc marked off by counting the corresponding number of minutes along the dial.

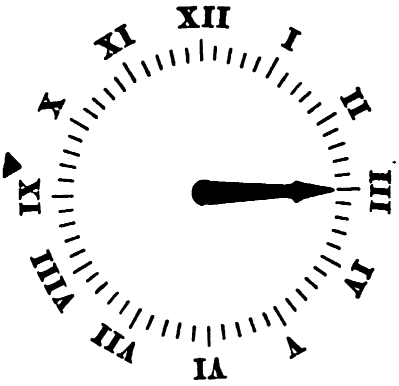
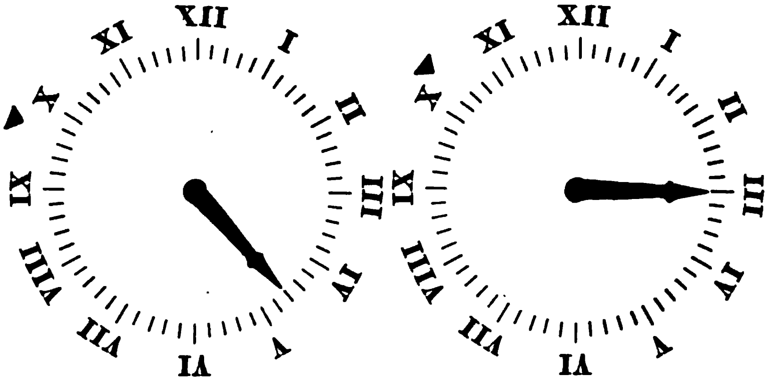


Fig. 1.
Time Stamp Record.

The inventor had thus gotten rid of the subtraction, but there were several desirable qualities not yet obtained. First, he could not tell from the record alone, whether it was the longer or the shorter arc marked off that was the measure of the period. For instance, he could not tell whether the period was 7 or 53 minutes. This was because the two hand or pointer imprints were exactly alike except in position. So he conceived the idea of making the pointer imprints different in appearance, by providing the pointer die with a mark in line with the pointer, as illustrated in Fig. 4.

The mark and pointer revolve together and either the dies or the platen are so arranged that the mark can be printed without the pointer at the initial imprint and the pointer at the final imprint as in Fig. 5, the mark being printed or not at the final imprint, as desired. This could be done either by allowing the pointer die or the corresponding portion of the platen to remain retracted from the paper during the first printing.



9:23 Fig. 2. 10:15

Initial Time Stamp Record. Final Time Stamp Record.

Elapsed Time: 10:15−9:23 = 52 minutes.

To read this record, hours and minutes must be subtracted from hours and minutes, an operation liable to much error.

It could thus be told with certainty from the record alone whether the longer or the shorter arc is the measure of the period, because the beginning of the arc is that indicated by the imprint of the mark without the pointer.

There was still something to be desired. The counting of the minutes along the measuring arc was a waste of time, if the value of the arc could in some way be directly indicated. If the hand were set back to 12 o'clock for the initial imprint, the final imprint would show the hand pointing directly at the minute whose number on the dial is the value of the period' and it would not even be necessary to count. But the setting of the hand back to zero would prevent its making the final imprint of any previously begun record, so that the machine could only be used for one record at a time. It was desirable to have a machine that would record any number of overlapping intervals at the same time, so that one machine would record the intervals of all the telephone conversations under the control of a single operator, or rather of two operators, because both of them could reach the same machine. So it wouldn't do to set the hand back to zero, as the hand must rotate constantly and uniformly. Then why not set the zero up to the

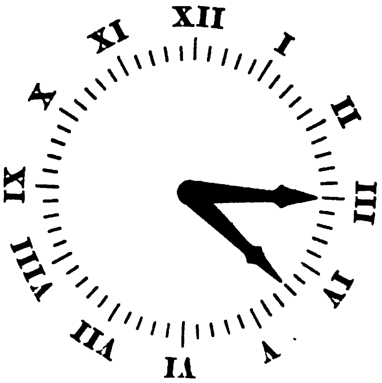


FIG. 3.
Subtraction eliminated but counting still required and uncertainty whether elapsed period is 7 or 53 minutes.

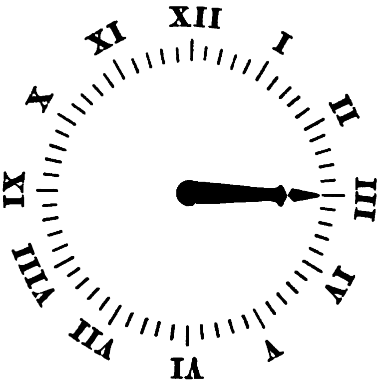


FIG. 4.
Hand and zero mark revolving within stationary dial.

hand at each initial imprint? This meant making the dial rotatable, as well as the hand. It gave an initial record like that shown in Fig. 6.

The inventor then thought of securing the dial to the pointer die so that they would revolve together, the zero of the dial being in line with the pointer, as illustrated in Fig. 7. This would obviate the necessity of setting the zero of the dial up to the pointer at the initial imprint.

But again the improvement involved a difficulty. As the dial rotated, its final impressions would never register with its initial impressions and would therefore always destroy them. As the first imprint of the dial was the only useful one, and a the second imprint only made trouble, the inventor conceived the idea of not making any imprint of the dial at the close of the period, and this he accomplished by making the annular portion of the platen covering the dial so that it could be advanced to print or not as desired. As the zero of the dial always marked the beginning of the measuring arc, it served the same purpose as the mark in line with the pointer, and the latter could now be omitted.

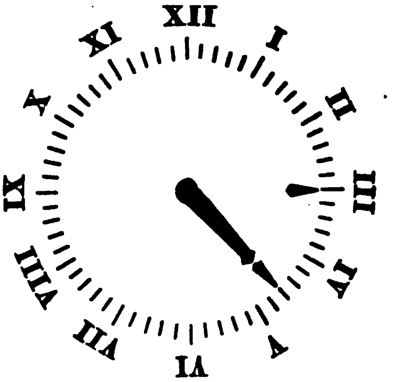


FIG. 5.

Initial imprint of zero mark alone and final imprint of hand (and zero). Elapsed time, 8 minutes. No subtraction and no uncertainty as to which imprint first, but counting still required.

The final machine then consists simply of a revolving die which, as shown in Fig. 8, consists of a graduated and progressively numbered dial, having a pointer revolving in line with the zero, and the machine has a platen consisting of an inner circular portion over the pointer and an annular portion over the dial, each portion being operated by a separate handle so that the dial can be printed at the beginning of the period and the pointer alone, at its close.

The final record has an initial imprint of the dial, Fig. 9a, the zero of the dial showing the position of the pointer at the beginning of the period, and a final imprint of the pointer alone, as shown in Fig. 9b, the complete final record, Fig. 9c, consisting of the superimposition of these two records, and showing the pointer in line with that graduation whose number is the value of the period. Here is a record not only involving no subtraction and no uncertainty but not even, counting in its record,

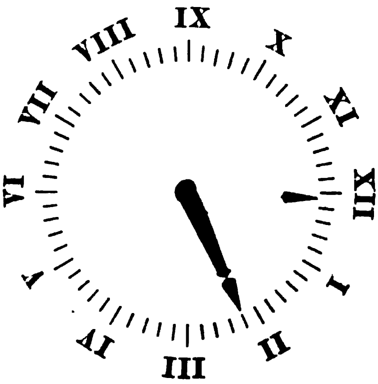


FIG. 6.

Dial moved up to initial position of zero mark. Elapsed time, 11 minutes. No subtraction, no counting, no uncertainty; but only one record possible at a time.

and, as it was made without disturbing the motions either of the pointer or dial, any number of records of other periods could have been begun or finished while the machine was measuring the period in question.

Hiding all the intermediate steps in the evolution of this invention, it seems the result of spontaneous creation, but considering the steps in their successive order, it will be seen that the invention is an evolution from the time-stamp; that logic rendered the effort of the imagination at any one step small by comparison, and that the individual steps might be well within the capacity of a person to whom the spontaneous creation of the final invention might be utterly impossible.

A most interesting example of the evolution of an invention is that of the cord-knotter of the self-binding harvester. The problem here was to devise a mechanism which would take place of the human hands in tying a knot in a cord whose ends had mechanically been brought together around a bundle of grain.

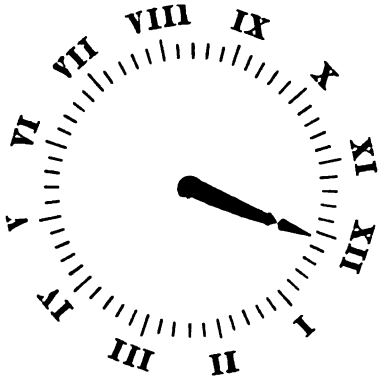


Fig. 7.
Dial with pointer at zero revolving together.

The first step was to select the knot which could be tied by the simplest motions. The knot which the inventor selected is that shown in Fig. 10, and is a form of bow-knot.

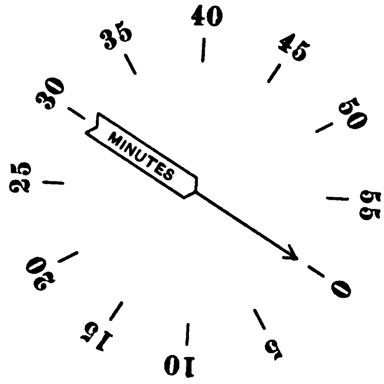


Fig. 8.
Dial with pointer at zero revolving together, zero mark on pointer being replaced by zero of dial.

The problem was to find how this knot could be tied with the smallest number of fingers, making the smallest number of simple movements. As anyone would ordinarily tie even this simple knot, the movements would be so numerous and complex as to seem impossible of performance by mechanism. The inventor, by study of his problem, found that this knot could be tied by the use of only two fingers of one hand, and

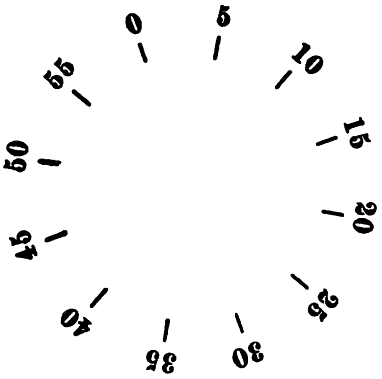


FIG. 9a.
Initial Imprint.

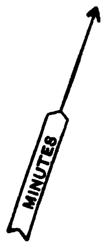


FIG. 9b.
Final Imprint.

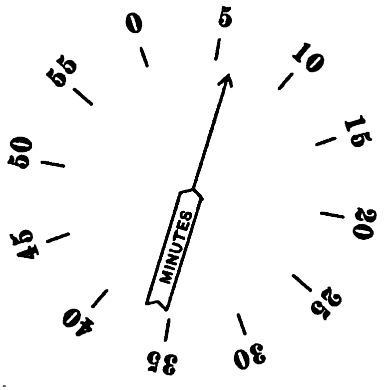


FIG. 9c.
Complete Record.

Simple, direct-reading record. No subtraction, no counting, no uncertainty. Any number of overlapping periods recorded on one machine.

by very simple movements. The knot will best be understood by following the motions of these fingers in tying the knot. Using the first and second fingers of the right hand, they are first swept outward and backward in a circular path against the two strands of the cord to be tied, as shown in Fig. 11.

The fingers continue in their circular motion backward, so that the strands of the cord are wrapped around these fingers, as shown in Fig. 12.

Continuing their circular motion, the fingers approach the strands of the cord between the twisted portion and a part of the machine which holds the ends of the cord, and the fingers spread apart as shown in Fig. 13, so that they can pass over and grasp the strands thus approached, as shown in Fig. 14.

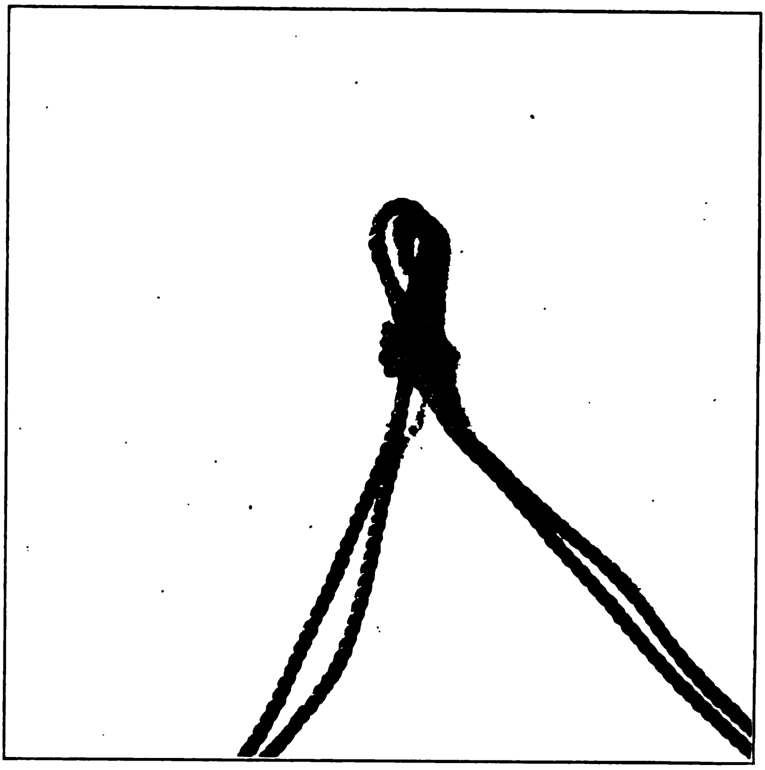


Fig. 10

The fingers then draw back through the loop which has been formed about them, the fingers holding the grasped portion of the strands, as shown in Fig. 15.

The knot is finished by the completion of the retracting movement of the fingers through the loop, thus forming the bow of the knot as shown in Fig. 16.

The inventor found that one finger could have a purely rotary movement, as if it were fixed on the arm and unable to move independently of the arm, and the movement being as if the arm rotated like a shaft, but the second finger must be further capable of moving toward and from the first finger to perform the opening movement of Fig. 13, and the closing movement of Fig. 14 by which it grasps the cord. The inventor accordingly, from his exhaustive analysis of his problem, and his invention or discovery of the proper finger motions, had further only to devise the very simple mechanical device illustrated in Fig. 17 to replace his fingers.

Fig. 11.

The index finger of the hand is represented by the finger *S*, which is integral with the shaft *V*. The second finger of the hand is represented by the finger *U*, which is pivoted to the first finger by the pin *s*. The grasping movement of the finger *U* is accomplished by a spring *V'* bearing on the shank *U'*, and its opening movement is caused by the travel of an anti-friction roll *U″*, on the rear end of the pivoted finger, over a cam *V″*, on the bearing of the shaft. The shaft is rotated by the turning of a bevel pinion *W* on the shaft through the action of an intermittent gear. The necessity of drawing the fingers backward to accomplish the movement between Figs. 14 and 16 was avoided by causing the tied bundle to have a motion away from the fingers as it is expelled from the machine, the relative motion between the fingers and the knot being the same as if the fingers drew back.

FIG. 12.

Thus the accomplishment of a seemingly almost impossible function was rendered mechanically simple by an evolution from the human hand, after an exhaustive and ingenious analysis of the conditions involved.

It will be seen from the examples I have given that the constructive part of inventing consists of evolution, and it is the association of previously known elements in new relations(using the term elements in its broadest sense). The results of such new association may, themselves, be treated as elements of the next stage of development, but in the last analysis nothing is invented or created absolutely out of nothing.

Fig. 13.

It must also be apparent, that pure reason and method, while not taking the place of the inventive faculty, can clear the way for the exercise of that faculty and very greatly reduce the demands upon it.

Where it is desired to make a broadly new invention on fundamentally different lines from those before—having first studied the art to find the results needed, the qualities of the material or other absolutely controlling conditions should be exhaustively considered; but at the time of making the inventive effort, the details should be dismissed from the mind of how results already obtained in the art were gotten. One should endeavor to conceive how he would accomplish the desired result if he were attempting the problem before any one else had ever solved it. In other words, he should endeavor to provide himself with the idea elements on which the imagination will operate, but to dismiss from his mind as much as possible the old ways in which these elements have been associated, and thus leave his imagination free to associate them in original and, as to be hoped, better relations than before. He should invent all the means he can possibly invent to accomplish the desired result, and should then, before experimenting, go to the art to see whether or not these means have before

Fig. 14.

been invented. He would probably find that some of the elements, at least, have been better worked out than he has worked them out. Of course, mechanical dictionaries, and other sources of mechanical elements and movements will be found useful in arriving at means for accomplishing certain of the motions, if the invention be a machine. Many important inventions have been made by persons whose occupation is wholly disconnected with the art in which they are inventing, because their minds were not prejudiced by what had already been done. While such an effort is likely to possess more originality than that on the part of a person in the art, there is, of course, less probability of its being thoroughly practical. The mind well stored with the old ways of solving the problem will, of course, be less likely to repeat any of the mistakes of the earlier inventors, but it will also not be as apt to strike out on

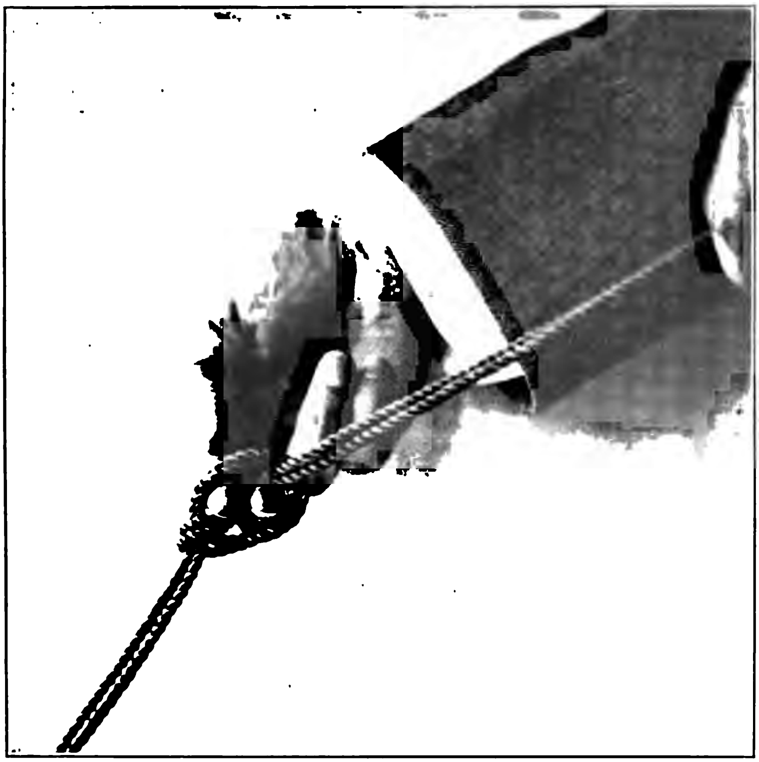


FIG. 15.

distinctly original lines. It is so full, already, of the old forms of association of the elements as to be less likely to think of associating them in broadly new relations.

Nothing should be considered impossible until it has been conclusively worked out or tried by experiments which leave no room for doubt. It is no sufficient reason for believing a thing won't work because immemorial tradition, or those skilled in

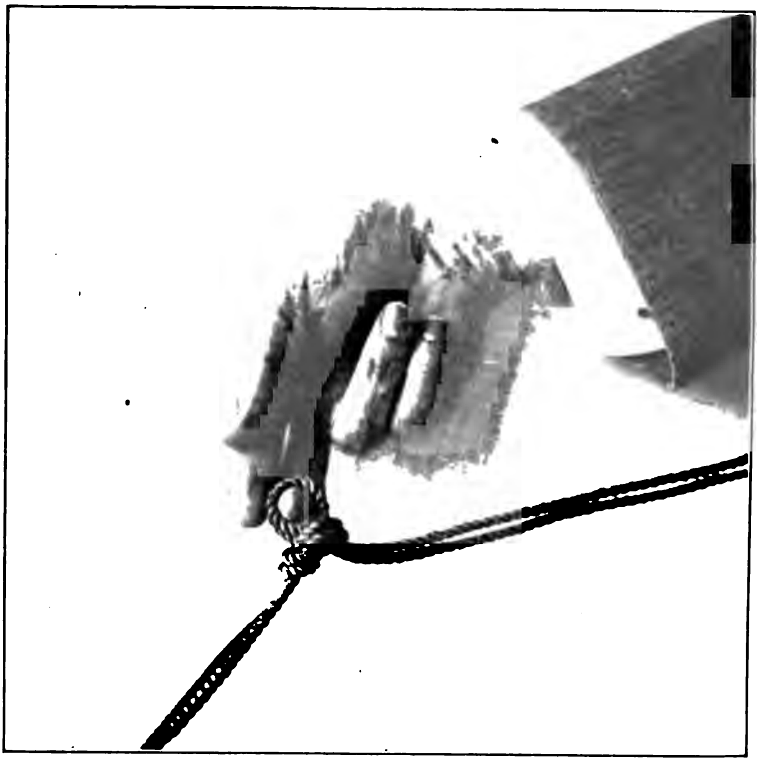


FIG. 16.

the art, say it will not work. Many an important improvement has been condemned as impracticable, by those in the art, before it has been tried.

A conception which an inventor has been striving for unsuccessfully will sometimes come to him at a time of unaccustomed mental stimulation. The slight stimulation of the movement of a train of cars, and the sound of music, have been known to produce this effect. The sub-conscious mind, after having been prepared by a full consideration of the problem to be solved, will sometimes solve the problem without conscious effort, on the part of the inventor.

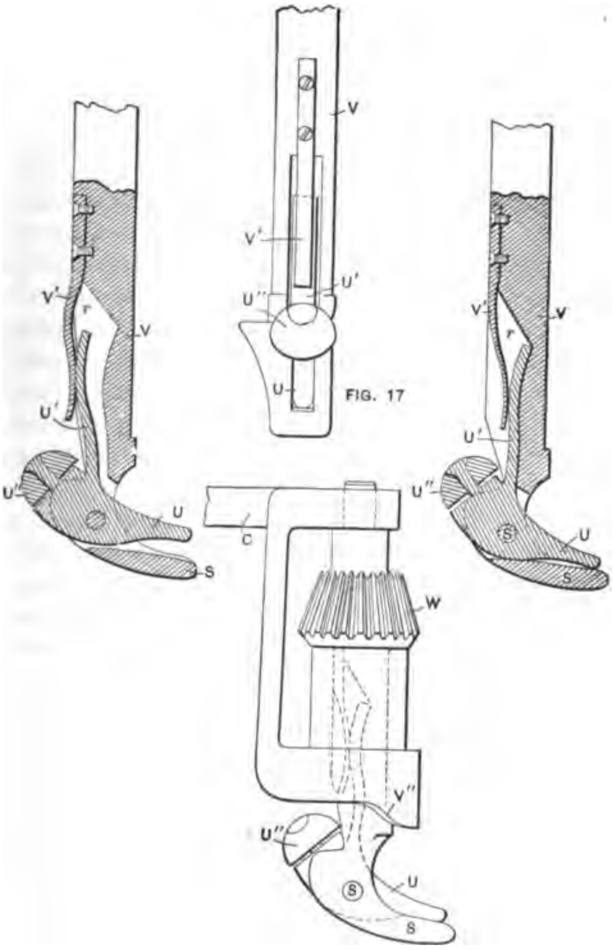


Fig. 17.
The essential parts of the cord-knotter.

In inventing a machine to operate upon any given material, the logical way is to work from the tool to the power. The tool or tools should first be invented, and the motions determined which are to be given to them. The proper gearing or parts to produce from the power each motion for each tool should then be invented. It should then be considered if parts of each train of gearing cannot be combined, so as to make one part do the work of a part in each train; in short, to reduce the machine to its lowest terms. Occasionally a mechanism will be invented which is exceedingly ingenious, but which it is afterwards seen how to simplify, greatly at the expense of its apparent ingenuity. This simplification will be at the sacrifice of the pride of the inventor, but such considerations as cheapness, durability and certainty of action leave no choice in the matter. It will sometimes be found that a single part can be made to actuate several parts, by the interposition of elements which reverse the motion taken from such part, or which take only a component of the motion of such part, or the resultant of the motion of such part and some other part. Where a machine involves the conjoint action of several forces, it can be more thoroughly studied, if it is found there are positions of the machine in which one force or motion only is in operation, the effect of the others in such position being eliminated, and thus the elements making up the resultant effect can be intelligently controlled.

The drawing board can be made a great source of economy in producing inventions. If the three principal views of all the essentially different positions of the parts of a machine are drawn, it will often be found that defects will be brought to light which would not otherwise have been observed until the machine was put into the metal.

It is desirable to see the whole invention clearly in the mind before beginning to draw, but if that cannot be done, it is often of great assistance to draw what can be seen, and the clearer perception given by the study of the parts already drawn, assists the mind in the conception of the remaining parts.

If the improvement which it is sought to make is a process, it should first be considered whether any radically different process can be conceived of, and if so, whether or not it is better than the old process, and the reason for its defects, and whether it is possible to cure those defects. If the old process appears to be in the right general direction, it should be considered whether one of the old steps cannot with advantage be replaced by a new one, or whether the order of performing the steps cannot be changed to advantage. I have in mind one process in which a reversal of the order of steps resulted in giving the product certain desirable qualities which had before been sought for, but could not be obtained.

It is sometimes desirable not only to invent a good process of producing a product, but to control all feasible processes of producing the product. Such a case occurred where the product itself had been patented, and it was desirable to extend the monopoly beyond the time when the patent on the product should expire. There were two steps or operations which were essential to the production of the product, and the inventor, by reference to permutations, saw that there were but three orders in which those steps could be performed; first, the order A-B, then the order B-A, and then both steps together. The order A-B was the old order, which did not produce an article having the desired qualities. The inventor therefore, proceeded to invent ways by which the steps could be performed together, and then by which they could be performed in the reverse order, and the patenting such two processes would cover generically all possible ways of making the article and secure the desired result of putting himself in position to control the monopoly after the patent on the article had expired, because no one could make the article without using one of his two processes.

In inventing compositions of matter there is one inventor who, if he is seeking for a certain result, will take a chemical dictionary and make every possible combination of every substance that could by any possibility be an ingredient of that which he desires to produce. It is as if he were seeking to locate a vein of mineral in a given territory, and, instead of observing the geographical and geological formation, and thus seeking to arrive at the most probable location of the vein, he should dig up every foot of earth throughout the whole territory, in order finally to locate the vein. This method is exceedingly exhaustive, but does not appeal to one as involving much exercise of the inventive faculties.

Inventing has become so much of a science, that if one is willing to spend sufficient time and money to enable a competent corps of inventors to go at the matter exhaustively, almost any possible invention involving but a reasonable advance in the art can be perfected.

DISCUSSION ON "THE ART OF INVENTING," AT MILWAUKEE, WIS., MAY 30, 1906.

C. P. Steinmetz: I do not quite agree with the author of this paper, or rather, I do not believe that there is such a thing as an art of inventing. I consider inventing as a part of the regular work of the engineer. The engineer has before him a problem to solve, whether it be a problem of design, installation, or operation. He has at his disposition a vast amount of experience, his own and others, and if he is successful he solves the problem in a number of successive steps. Some of these steps are old, and have been taken by others under similar conditions. One, or several, may be new, have never been taken by anybody before; that is, are invention, and as such are covered by patent. These new steps may not necessarily be the most important, the most difficult or ingenious ones, but they are new and as such are invention. But without being put in the position where the problem calls for just such a step, without having at his disposition the vast amount of preceding experience, the engineer would never have made that invention—perhaps he may have invented something else.

For the engineer, originality is essential to enable him successfully to solve problems or parts of problems by new ways, or ways partly new. But this part of an engineer's work is so inextricably joined with the rest of his work, that I see no reason to separate it as a special art called the art of inventing. Intellectually, it is neither higher nor lower than the rest of an engineer's work: the application of known facts and selection of appropriate known methods to the solution of a problem. Indeed, frequently the engineer finds a new way, and considers it inventing, though investigation afterwards shows that he is not the first, but that somebody else before him has made the invention, and he merely re-invented it. Nobody can know everything. So, in many cases, inventing is merely the incidental feature that that particular engineering step has not been taken by any one else in exactly the same manner; and similarly, other steps, though they may be more difficult, more creditable to the engineer, yet they are not invention.

As to the question of giving the credit to the inventor—I speak not of those broad and radical inventions, which are rare and far between, but of by far the largest number of patents—it must be considered that in most cases the problem was put before the inventor by some one else, or as part of his professional work; it was solved by the use of a vast amount of experience gathered by others, without which he could not proceed a single step, and very frequently that step which constitutes invention would be of no value whatever, except in connection with the rest of the work, and even then a great amount of development work may be needed to reduce the invention to practical value. That is, the new idea, while it is an invention, requires a great deal more, before it is of commercial utility, and to claim for the inventor all the credit for the advance in the art resulting from the invention, is as unjust as it would be not to give any credit for inventive originality.

I repeat, most inventions are engineering steps, part of the regular work of the successful engineer, who must possess not only the knowledge to use old ways and methods, but also the originality to find new ways when required to solve the problem before him.

There are but few pioneer inventions. It occasionally happens that inventions are made which open up an entirely new field, establish a new industry, as the invention of the incandescent lamp, of the wireless telegraph, of the polyphase system. And frequently it is difficult to state the exact feature of which the invention consists, especially when after the lapse of years the inventor's work has become commonplace to the world. Take for instance the case of the Edison incandescent lamp. This is one of the most useful, important, and radical inventions. It perhaps can be said to be the foundation of the electrical engineering industry. Before that, electrical engineering was only the art of telegraphy; after that electric power became a quantity to consider. But before Edison people had run filaments in a vacuum. Carbon filaments had been proposed. The high-resistance-feature of the filament is difficult to consider as an essential distinction, since it is merely a quantitative difference: as long as the source of electric power was a primary battery of low voltage, a high-resistance filament would have been decidedly disadvantageous—low resistance wanted. With the source of power of high voltage high resistance was wanted; that was self-evident, especially after Edison had done it. To lead the current into a bulb, platinum wires had probably been used before Edison. So you may ask: What is meant by the invention of the incandescent lamp? That is a question for lawyers to discuss; and since the patents have expired, the details are of no further interest. But before Edison, incandescent lighting did not exist. As the result of Edison's work on the incandescent lamp, an industry of vast importance has been created, and a revolution brought about in the methods of illumination. The importance of the problem was realized before Edison. But whatever may be the details of the work, nobody did it before, and to the one who made the incandescent lamp what it is to-day, the historian gives the credit.

Again we see the same thing in the matter of polyphase transmission. Polyphase currents had been used before Tesla; investigations had been made by Ferraris. Motion had been transmitted synchronously, by polyphase currents, many years before Tesla. All the engineering world was striving for an alternating-current motor; and still all the world waited until Tesla showed how by polyphase currents *power* could be transmitted and distributed, not merely a laboratory toy set in rotation, but power transmitted over distances to do the world's work.

It is characteristic of most pioneer inventions that at first people do not believe that it has been done; do not believe it can be done; pay no attention to it; laugh at it. Next, a host of claimants crop up, all of whom have solved the problem, made the invention long ago, and they claim the credit—only nobody knew of their work until the inventor showed the way. Next, people claim that the things is as old as the hills, is no invention at all; it was long known before the inventor used it, but somehow nobody had used it before. Ultimately, history records that the art did not exist before, that the work of the inventor brought it into existence, and that to him belongs the credit. Usually he gets the credit long after his death.

This applies to men that produce radical inventions. The reverse of this is the professional inventor, the man who hunts around to pick up and combine ideas created by others, whether useful or not, merely for luck, because sometime something similar may be made useful by the inventions of others. Him I consider as just a step above the professional promoter. But between the two, the pioneer and the freebooter, stands the vast majority of legitimate engineering inventions, representing steps in useful engineering work done for useful purposes.

President Wheeler: I quite agree with what Dr. Steinmetz has said, and at the risk of making an anticlimax I will go back for a moment to the subject of the paper, because I want to mention another example of a much needed invention. The author of the paper says that the first requisite is to select a problem. In nearly all work and all businesses a great deal of time is spent in multiplying a unit price by a quantity, and writing the result on a ticket, either a time ticket, a material ticket, or a cash ticket. I think it is hardly realized how much routine labor is spent in writing these tickets, and, as a bookkeeper would say, in making the extensions. In these days when adding machines and multiplying machines are coming into use, the tendency to use mechanical devices in all bookkeeping operations is getting stronger all the time.

I wanted a machine to do the operations I have just referred to, and I asked the people who make the calculating machines to make one for me, but they were not able to do so. I call it a multiplying printer. It might consist of three dials, or equivalents—if you set one at 13 cents and the other at 109 lb., the third dial would tell how much this comes to. If you put a regular form of ticket under it and strike it, it will print the product, and also print the unit price and the number of pounds. The object of printing all three is so that you may go back and see where the mistake was when some one makes out a ticket wrong. That sounds quite simple, and yet nobody has turned out such a device. I thought I would invent one to order, three or four years ago. I consulted a mechanical expert and asked him to get it up for me. After a few days he called on me and laid on my desk what he called the literature of the subject—a bundle containing about 500 patents of similar devices, and told me he would be glad to get up the machine at $50 per day, but could not tell how many months it would take.

Edwin J. Prindle: Mr. Steinmetz's report of his remarks at the convention, concerning my paper on the "Art of Inventing" has been modified so that my oral reply to it does not appear to have complete connection with the matter, but as those who were present at the convention and who remember the matter will retain the impression of his remarks as they were actually delivered, I desire to make the following more complete reply to Mr. Steinmetz's remarks.

Mr. Steinmetz' position was that inventing is a mere incident of engineering, and that inventing, considered by itself, is one of the forms of activity which is least worthy of respect. The engineer is doing engineering *per se* when he is designing structures and apparatuses for new situations and conditions without changing their principles. When, however, he is introducing new principles of operation, he is inventing, as distinguished from practicing engineering proper. Mr. Steinmetz seems to think that it is the same grade of work to select from among known apparatuses that apparatus best suited for a given condition, and to determine its size and proportion by the use of mathematics and engineering rules already in existence, than it is to invent an apparatus working upon a new principle and doing work at perhaps a greater economy than any apparatus previously invented or serving a purpose which no apparatus previously known can serve. To state Mr. Steinmetz' position, seems almost to answer it.

Sir Francis Bacon considered inventing as one of the highest forms of effort. He said:

> The introduction of great inventions appears one of the most distinguished of human actions, and the ancients so considered it; for they assigned divine honors to the authors of inventions, but only heroic honors to those who displayed civil merit; such as the founders of cities and empires, legislators, the deliverers of their country from lasting misfortunes, the quellers of tyrants, and the like. And if anyone rightly compare them, he will find the judgment of antiquity to be correct; for the benefits derived from inventions may extend to mankind in general, but civil benefits to particular lands alone; the latter, moreover, last but for a time, the former forever. Civil reformation seldom is carried on without violence and confusion, while inventions are a blessing and a benefit without injuring or afflicting any.—*Novum Organum*, Book 1, Section CXXIX.

To take the view of a man of to-day, Judge Grosscup, a distinguished Federal Judge in Chicago, has said;

> Inventive genius has given to mankind most of its present material civilization. The magnificent flower of civilization, everywhere surrounding us, has opened from germs that were fructified from the brains of inventors.

The founders of the Constitution of the United States thought inventing so important that they introduced a provision into the Constitution for the enactment of laws for the protection of inventions.

George Washington was sufficiently interested in the stimulation of invention to urge in his first annual message to Congress the expediency of giving effectual encouragement to the introduction of new and useful inventions. In fact he took the trouble to sign the first patent ever issued by the United States, and other subsequent patents.

Photographs of a patent signed by George Washington will be found in an article by the writer in the *Scientific American*, May 13, 1899, page 300 Not only was the patent signed by George Washington, but it was signed by the Secretary of State, and the Attorney General of the United States.

The inventor is one of the greatest benefactors of mankind, and there is eminent authority for belief that, as a class, the benefit which inventors confer upon humanity is a powerful incentive to the production of inventions, as well as the profit that may come to them. Senator O. H. Platt of Connecticut, in an address delivered before the Patent Centennial Celebration, 1891, said:

> I deny, however, that the hope of pecuniary gain is the only motive of invention, or indeed the most powerful motive. Two others, at least, are more potent: The insatiable desire to man to see the invisible, to touch the intangible, to know the unknown, to conquer the unconquered, is one; to benefit the human race is the other. The prospect of money reward alone would never absorb and concentrate and intensify the faculties of the inventor. * * * If they can but discover the germs of new inventions which are to cheapen production, which are to minister to the present and prospective wants of mankind, they will be satisfied with their life-work and feel that they are entitled to a place among the world's great doers, though others shall enter in and reap more abundantly the money reward. There never yet was a true invention from which the public did not reap infinitely greater pecuniary reward than the inventor. However selfish his purpose may be, it is an inevitable law of invention that it holds greater benefits in store for the masses than for the inventor.

Every physical contrivance that is substantially different from things previously known, is the result of invention. The comfort in which we live, the ease with which we communicate with each other, the labor-saving devices which make it possible to maintain physical life without ceaseless effort—these are the result of invention, and they give the opportunties necessary for the building up of our present civilization, so that fundamentally inventing is the most important of industrial activities. Inventing creates that which did not exist before, and does not consist in merely repeating actions which others have shown how to perform or in participating in the activities of others as a mere agent or assistant, and, therefore, inventing is, as is almost universally recognized, one of the forms of activity worthy of the highest respect.

That which is easy for us to do, we are apt to hold in light regard. When we thoroughly understand a difficult subject so that it holds no mystery for us, it is apt to suffer in our estimation. It requires an effort to withdraw one's self to a sufficiently distant point of perspective to restore a true estimate It is probably for this reason that Mr. Steinmetz so lightly regards the dignity of inventing. Inventing comes so easy to him, that he forgets its tremendous importance, and it seems to him but a mere incident in his engineering. Because of the facility with which he invents, he is probably one of those least qualified properly to estimate the dignity of inventing.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

SHUNT- AND COMPOUND-WOUND SYNCHRONOUS CONVERTERS FOR RAILWAY WORK.

BY W. L. WATERS.

The question of shunt- or compound-wound excitation for synchronous converters has been discussed so much that it is of interest to compare the relative merits of the two. As the shunt winding is obviously the simplest and cheapest and most convenient way of exciting a synchronous converter, it would be well to begin by considering why a compound winding is ever used.

In a direct-current circuit it is often an advantage to have a system which is to a great extent self-regulating as regards voltage. This is especially the case where the load changes frequently, and in such cases a compound-wound generator is used. A series winding on the generator field-coils tends to make the voltage at the generator terminals rise as the load comes on the machine. This rising tendency is used to counteract the increasing voltage drop in the feeders and mains due to increasing load. By changing the series winding on the generator the rising tendency of the terminal voltage can be varied to almost any extent.

In a synchronous converter the ratio of the voltages at the terminals of the two sides of the machine is approximately constant, and independent of the load on the machines or the magnitude of the excitation; that is, when transforming from alternating current to direct current, the direct-current terminal voltage bears an almost constant ratio to the alternating-current terminal voltage under all conditions. So the only way of varying the direct-current terminal voltage is to vary the alternating-current voltage supplied to the machine. If the direct-current voltage is to rise as the load comes on the machine, then the alternating-current voltage which is supplied to the machine must be made to vary in the same way. Assuming that approximately constant voltage is supplied at the generator end of the alternating-current feeders, and that the circuit between the generator and the synchronous converters contains sufficient inductance, then the voltage at the synchronous-converter end of the alternating-current line can be raised or lowered by introducing a leading or a lagging current into the system. A leading or a lagging current can be introduced into the system by over- or underexciting the converter. So by putting a series winding on the magnets of the converter the excitation of the machines will be increased as the load comes on, and a leading current approximately proportional to the load introduced in the alternating-current system. This will tend to raise the alternating-current voltage supplied to the converter and, in consequence, the terminal voltage at the direct-current side. By means of this system, a synchronous converter can be compounded in a manner similar to that employed for compounding a direct-current generator. The voltage at the direct-current terminals can be made to increase as the load comes on.

Here then is a system that gives automatic control of the voltage as the load varies. Such a system is obviously extremely useful and convenient. Unfortunately, this system presents a number of disadvantages in practice: a series winding is needed on the converter magnets, artificial reactance coils are practically always needed to insert in the alternating-current line so as to bring its reactance up to the required value, and there is need for extra switchboard arrangements. This means increased complication and cost, and a loss of efficiency. A compound-wound converter costs about 7 or 8% more than a shunt-wound converter. Reactance-coils usually cost about 5% of the cost of the converter. The efficiency of the system is lowered probably 1 to 2%. And in addition the system is more complicated, and in consequence more liable to break down. There is also liable to be trouble in operating the system. A series field winding on a synchronous converter is always a source of danger on account of the liability of its reversing. When starting a converter, the series fields can be short-circuited and the danger at that time avoided; but if the attendant forgets the short-circuiting switch at any time, there is liable to be trouble. And if at any time when the series coils are in use the alternating-current supply fails or is cut out, and the machine is left connected to the direct-current circuit, the series coils will reverse and the converter is likely to run away, especially if the direct-current voltage is varying. A speed-limit device should take care of this, but as automatic devices usually go wrong when they are most needed, so the fact must be accepted that a series winding introduces a possible source of serious trouble in any synchronous converter system.

The automatic compounding obtained by a series winding and reactance-coils is not so satisfactory as would be expected. It is natural to expect that the most useful application of this system would be to over-compound converters in a small sub-station, to compensate for a large feeder-drop in case where the load fluctuates violently. The results in such a case are, however, not always satisfactory.

To over-compound a converter and to change the voltage at the direct-current side means that the magnetic flux in the field magnets of the converter must change; as solid-steel field magnets are always used in converters the magnetism cannot change quickly, there is therefore often a considerable time-lag before the voltage changes to correspond with the change in load. The result of this is that when the load is varying quickly the voltmeter needle is kept wandering aimlessly about the scale, indicating anywhere from, say, 500 to 650 volts, the voltage apparently not having any relation to the load on the machine. However when the converter is flat-compounded instead of over- or under-compounded the result is more satisfactory, as the natural tendency of the solid poles is to hold the magnetism and voltage constant.

Usually, however, small sub-stations are supplied from comparatively small power stations; and with a varying load on the converters one of the main effects noticed in the sub-station is the fluctuation of the speed of the engines, and consequently the speed of the converters and the alternating-current voltage. The effect of this variation in speed often completely masks all the results of the compound winding.

In addition, this method of compounding is often a nuisance. There must be careful adjustment of the series winding and of the reactance-coils at the sub-stations before getting the desired effect. Then if the converters are changed to another station, or if the line conditions are changed, the adjustment has to be made again. If other compound-wound converters are installed in the same sub-station, there is trouble to adjust them so that they divide the load properly at all loads. Equalizer connections are used, but the results are rarely altogether satisfactory. The different characteristics of the converters, and the variation in the brush-contact resistance, and the temperature of the machines—all tend to upset the adjustment. If shunt-wound converters are not dividing the load properly, varying the field rheostat will quickly adjust the load. And in any case shunt-wound converters, just like shunt-wound generators, have a much greater natural tendency to divide the load properly than have compound-wound machines. With this automatic compounding, the power-factor of the converter system varies, and often varies widely, with the load. The power-factor cannot be interfered with without upsetting the complete system of regulation. A shunt-wound converter tends to keep the power-factor the same at all loads. In any case the power-factor can be adjusted by means of the field rheostat, without in any way upsetting the regulation.

The result of all the complication and disadvantages of a compound-wound converter with reactance-coils, is that often after the system has been in operation for some time the series magnet-coils and the reactance-coils are cut out and the converter is run as a straight shunt machine. The machine is then more in the control of the operator and is less liable to give trouble.

Probably the best system for general work is to have shunt-wound converters, standard transformers, and no reactance-coils. Somewhat over-excite the converter so as to keep the power-factor a leading one at all times, and then leave the machines to take care of themselves, only adjusting the excitation in case they fail to divide the load properly.

In the case of a large station the feeder drop is small and the fluctuations in load are unimportant, so that the voltage keeps fairly constant at all times. The only work, then, for the attendant is to cut in or out an extra converter as the load requires it, and to see that each converter in circuit carries approximately its proper proportion of the load.

In the case of small sub-stations, the voltage will vary with the load on account of the feeder-drop. The direct-current voltage will be high on light loads and will fall on full load, For a line with sub-stations at various points this is an ideal condition. When the load is light on such a station it will mean that most of the load on the system is being carried by other stations. The voltage will then be high at the lightly loaded station and lower at the more heavily loaded stations. The lightly loaded station will then tend to help out the heavily loaded one, resulting in ideal conditions—a tendency to distribute the load proportionately between the stations at all times. The converter should be excited so as to get either unity power-factor or a leading power-factor at all loads, and then the feeder drop will automatically take care of everything else and there will be a tendency always to divide the load proportionately between all the stations.

Thus with shunt-wound converters instead of compound-wound machines with reactance-coils, there results a cheaper, more efficient, and less complicated outfit, an outfit less liable to give trouble and which will give better results both in large and in small stations. It is hardly to be wondered at then that the present tendency is to make all converters shunt wound. And I think the time is not far distant when the compound-wound converter will be considered as a special type of machine to be used only to meet exceptional requirements. The shunt-wound converter will then be standard for all railway work.

DISCUSSION ON "SHUNT- COMPOUND-WOUND SYNCHRONOUS CONVERTERS FOR RAILWAY WORK," AT MILWAUKEE, MAY 30, 1906.

J. B. Taylor: Mr Waters' statement of the tendency to leave off the series field windings of synchronous converters for railway work is either in the nature of a prophecy, or else he has not compared the number of plants operating with compound windings with those operating without them.

For large city systems where there are a great many cars, and the load changes gradually (depending on the hour of the day), shunt-wound converters are used in some cases, as they have the advantage of simpler connections and there is not much to be gained from the compound winding. On the smaller systems, and also on the largest system, where there are sudden changes in the load, there are a number of decided advantages to be gained by placing the series field on the converter. This has been the practice for a number of years past, is still the practice, and I am satisfied will still continue to be the practice until something quite different comes up.

The principal advantage of the compound winding is the more or less automatic compensation for line-drop, so as to maintain approximately constant direct-current voltage at the sub-station. There are some incidental advantages, such as the ability to secure desired division of load between machines, and saving of time in starting and placing machines in service. Machines having different characteristics, if they are shunt-wound machines, will sometimes give considerable difficulty in obtaining the desired division of load, whereas, with compound-wound machines an adjustment of shunt on series field will permit the operator to divide the load in the desired manner. The converters may be started at four o'clock in the morning, and run until two o'clock the next morning without touching the field rheostat. When starting a converter from the alternating-current side, a small field excitation will make the converter lock in step with synchronous speed with correct polarity. This separate excitation is given by the series field on closing the equalizer switch, provided another machine in the station is carrying a load.

There should be no marked increase in cost due to the series field winding; there is no more copper on the field, and what copper there is used is to better advantage, as it is obvious that a large copper strip with a small amount of insulation can be placed more effectively than a small winding insulated for 500 or 600 volts.

As far as the efficiency of the converter itself goes, there is no reason why the series field should involve increased losses. It is true, the use of a reactive-coil involves certain small losses, but these are more than compensated by the advantages. If the reactive-coil has a kilovolt-ampere rating that is 15 per cent. of the converter rating, and even if the losses in this coil are as large as 5 per cent. of its rating at full load on the converter, this loss would be only 0.75 per cent. of the converter rating. At light load the reactive-coil loss is practically nothing.

The series field is of especial benefit on the small system where the fluctuations in the load are felt at the generator. The tendency of the increased leading component on the converter, due to the series field, reacts on the generator and tends to keep the voltage up. As a result we find that the small systems operate with very little attention to the voltage. They are started up, and as the load comes on, the generator voltage, instead of falling seriously, tends to remain constant. The result of this is that we get fairly constant voltage at the sub-stations; and while in railway work only fairly constant voltage is required, it is better to have the voltage stay between 590 and 610 volts, than to drop from 600 down to 550 or 525.

Besides maintaining the schedule, the maintenance of voltage reduces consumption of energy, as anyone knows who has figured the watt-hour consumption of a car. In order to make a low watt-hour consumption the voltage must be kept up.

On most systems the substations are so far apart that it is impracticable to count on one relieving another to any great extent. It could be done at the expense of a great amount of copper or by having the converter voltage fall off very rapidly with increasing load.

There is a special case, in one of the French cities, where the character of the load is somewhat the same as we have in New York on the elevated system, where many trains and heavy loads are on all the time, and where the sub-stations are quite close together. In this case it is desirable to have the load shared by the sub-stations because the feeder-drop between them is comparatively small. In that case they have the series field winding, but reverse it so that the converter will purposely have a very drooping characteristic and one sub-station is relieved by those adjacent to it. Cases like this are quite special. As I said at the outset, the compound winding is in general use and there appears to be no present tendency to dispense with it.

P. M. Lincoln: I agree with Mr. Taylor in taking exception to the conclusions reached by Mr. Waters. The shunt-wound synchronous converter and the shunt-wound generator have much the same characteristics. They both have the drooping voltage characteristic, they differ in degree only, the shunt-wound converter will not drop its voltage so much with increasing load as will the shunt-wound direct-current generator, but the drop is there. Where a rising voltage characteristic is desired on account of operating conditions, it is necessary, of course, to have the compound-winding. The compound-winding does not add materially to the complication or to the cost of the system. The additional cost is practically all in the switchboard apparatus, principally in the necessity of using equalizer switches, etc., but that, as will be recognized, is a small portion of the total cost.

By properly designing the transformers which connect to the converters; that is, by introducing the proper amount of inductance, the necessity for reactance-coils can be entirely avoided. As a matter of fact it is avoided in the standard construction of some of the manufacturing companies. As to load distribution between converters, Mr. Waters says that this is not good with compound-wound converters. I believe the equal load distribution between converters is not so much a function of the compound winding as it is of other elements. If a number of converters are operated from the same low-tension bus-bars, the brush tension, brush friction, and other small irregularities will cause a considerable difference in the distribution of the load. If, however, between the high-tension bus-bars, the point of equal potential on the system and the converters, there is placed a sufficient amount of inductance, as is the case when each converter is fed by its own group of transformers or its own secondary windings in a group of transformers, then the difficulties in load distribution disappear. That is the logical way of operating. Where the rising voltage characteristic is wanted, it is perfectly easy to supply it; where it is not wanted it is easy to leave it off. There is no particular difficulty in doing it. One instance which I might state which will show the contrary of Mr. Waters' statements as to modern tendency, is the case of the Manhattan Elevated Railway in New York. Originally they put in their converter stations and operated them for a number of years as straight shunt-wound converters. However, within the last few months, or possibly a year, the practice in this group of stations has been changed and the converters are now operated compound wound.

W. L. Waters: Mr. Taylor says that there is no difference in cost between a shunt and compound-wound converter. Speaking as a designer, I can say a compound-wound converter costs about 6 or 7 per cent. more than a shunt-wound converter. In order to get automatic compounding, a compound-wound converter has to be designed so that it can introduce a large leading current into the line; that is, it must be capable of being highly overexcited. A shunt-wound converter, on the other hand, is designed to run on unit power-factor and to have a normal excitation. A compound-wound converter is designed so that it can be run with from 30 to 50 more ampere-turns in the field than a shunt-wound converter. This means that there must be from 30 to 50 per cent. more copper on the fields, and space must be allowed for this extra copper. This makes the frame bigger and the whole machine heavier. Mr. Taylor may possibly have confused factory cost and selling price. I was speaking entirely of factory cost. The price at which a machine is sold is entirely a commercial question and has nothing whatever to do with the factory cost.

Referring to the question of efficiency; as I have stated above, a compound-wound converter usually has from 30 to 50 more ampere-turns on the field. This means that the loss in the field-coils is from 30 to 50 per cent. greater than in a shunt-wound converter. This is one place where efficiency is lost; the other is in the reactance-coils.

Referring to Mr. Lincoln's statement that the use of reactance coils can be avoided by designing the transformers with sufficiently high self-induction; this can certainly be done. It will mean, however, that the transformers are no longer standard, and that all the adjustment of the compounding has to be done on the series winding, which will mean again that the series winding has to have a bigger margin allowed so as to get this adjustment.

Both Mr. Lincoln and Mr. Taylor misunderstand me if they think I contend that general practice is toward the use of shunt-wound converters. I meant to say that when the points of extra complication increased cost, reduced efficiency, and less reliability are considered by the operating engineer, he will usually come to the conclusion that the shunt-wound converter is preferable.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906

ECONOMIES TO BE DERIVED FROM THE UTILIZATION OF WATER POWERS OF LOW HEAD IN THE CENTRAL WEST.

BY DUGALD C. JACKSON.

The necessity for the utmost reduction in the cost of their product is being pressed more determinedly upon the electric generating companies located in the smaller cities of the central west as the use of the electric current becomes more generalized. The extension and generalization of the use of current also goes hand in hand with, and is encouraged by reduction in the cost of the plant output, since a generating company may obviously increase its sales at a rapidly accelerating rate as the price of its product falls.

It is well known to engineers familiar with the conditions of the central west that the electric plants of the cities of medium and smaller size have, until recent years, been of characteristically unsubstantial construction, and the operating expenses have been proportionately high.

I propose to tell briefly something of the way in which the electric light company in one of these smaller cities, namely, Janesville, Wisconsin, a city of about 15 000 inhabitants, has improved its condition by getting away from the old-time uneconomical plant to a plant of modern construction which is substantial, and is capable of producing current with so much economy that the use of the product has extended enormously during the last three years. I take the situation in Janesville for the subject of this paper because of the unusual fact that the company has been able to utilize three separate water powers, two of which are used for continuous service, and the third for peak-load service.

Three or four years ago the Janesville Electric Company was operating a power house in the heart of the city, and was there utilizing a small amount of water power in conjunction with a considerable amount of steam power, of which the latter was generated under conditions of much inconvenience and lack of economy. The company also owned a small water power some miles from the city, and it utilized this for operating a synchronous motor in the city station and the like.

The company came into hands with financial strength and keen foresight, and it obtained nearly exclusive water rights at two dams on the Rock River, located within the limits of the city of Janesville.

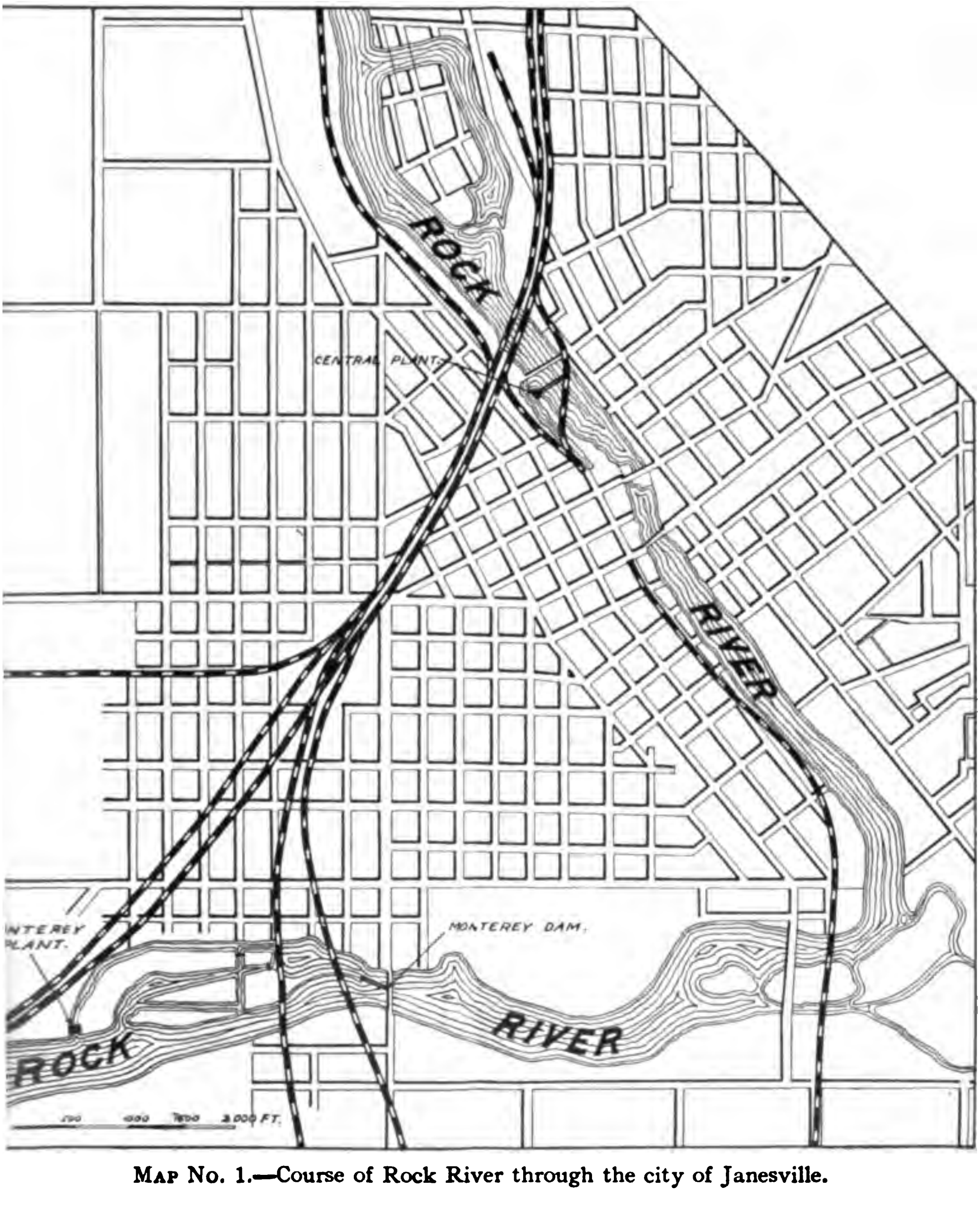
An examination of Map No. 1 shows that the Rock River flows from the north into the city of Janesville, makes an easy easterly turn, and then swings sharply toward the west before it leaves the limits of the city. As it makes its turn through the city, it also makes a rapid drop in level.

At a point which is a few blocks from the business center of the city, there is an old timber dam which has long been used to develop water power that was originally utilized for running a grist mill and other like purposes, a canal of some length having been extended along the margin of the river through a portion of the city. The electric company obtained water rights for the greater portion of the power on this site, and also the site of the old grist mill upon which the company has erected a modern fireproof power house. This is the Central plant named on the Map.

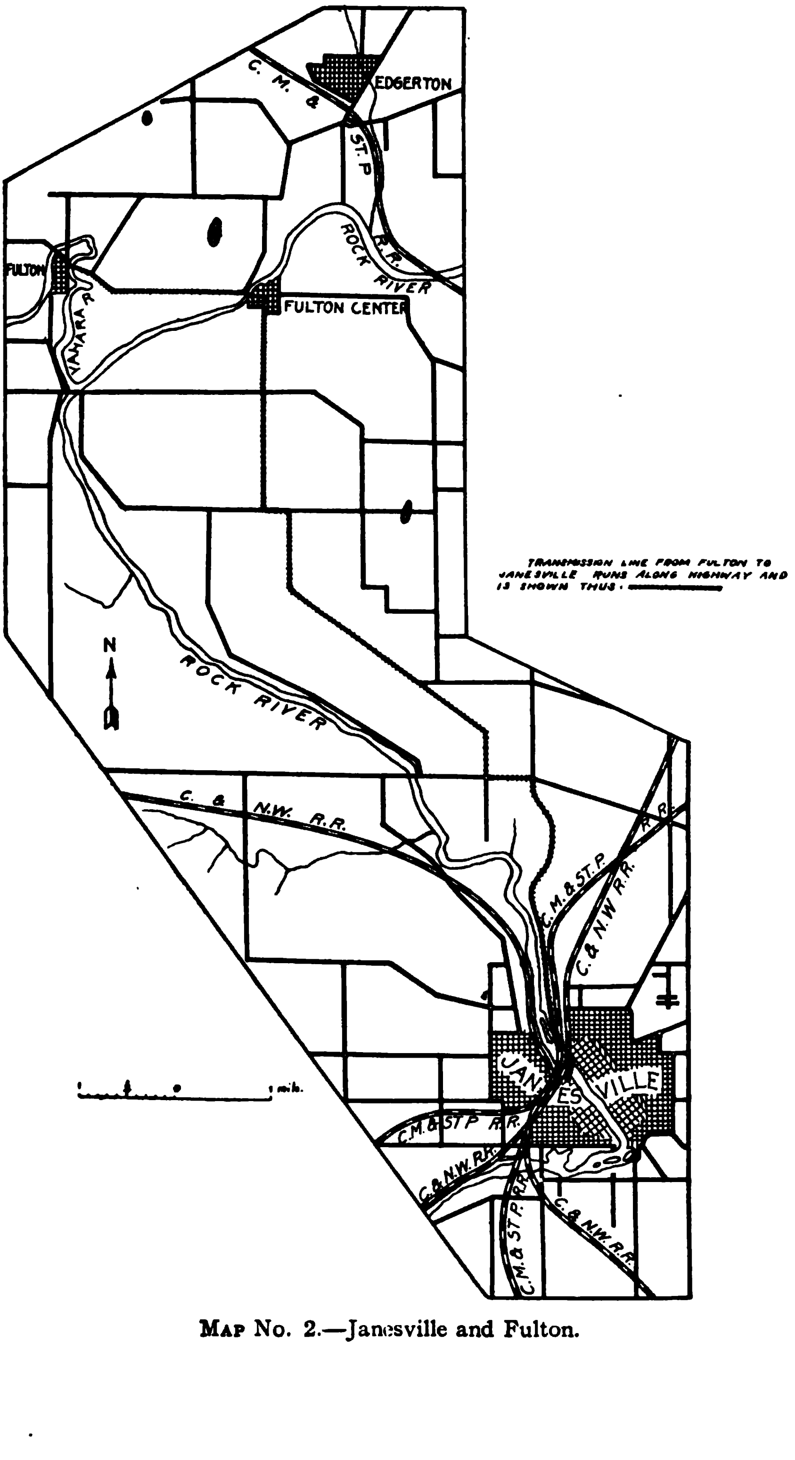
Just southwest of the point where the river turns sharply westward before leaving the limits of the city, is an old timber and stone dam, which has been in existence many years. It formerly supplied power to a woolen mill, and of recent years also furnished the power for operating a cotton mill; but the cotton mill was closed down, and the Janesville Electric Company was enabled to obtain its site with power plant and the greater portion of the water rights at this dam. This is the Monterey site which is marked upon the Map No 1.

The third water power is a small power about 12 miles from Janesville, the water rights of which are owned exclusively by the company. This is the Fulton site which may be seen on Map No. 2.

I will denominate the plants at these three power sites respectively as the Central plant, the Monterey plant, and the Fulton plant.



Map No. 1.—Course of Rock River through the city of Janesville.



Map No. 2.—Janesville and Fulton.

Upon securing the water rights and the mill site where the Central plant now stands, the Janesville company placed the development of a suitable electrical generating plant in the hands of engineers, The condition of the site at that time is indicated in the photograph marked Fig. 1. The old mill was torn down, a suitable forebay excavated, reinforced concrete penstocks erected, suitable waterwheels installed, and measuring gates erected at the entrance to the forebay. The measuring gates are large movable gates which are required because the electric company does not own quite all of the water rights.

FIG. 1.—Upper dam and site of present Central plant, showing old grist mill.

They were installed under the direction of the county court for the purpose of properly dividing the water between the owners in accordance with their proportionate ownership. The condition of the site while this work was going on is indicated by the photograph marked Fig. 2. Fig. 3 shows the site after the completion of the power house.

In passing, I will remark that the concrete work for the penstocks was prosecuted in midwinter with the temperature at times 12 to 16 degrees fahr. below zero, but careful precautions were taken and the concrete has proved exceptionally free from defects.

The dam at the Central plant affords a head of 8.5 ft. at normal water, which is somewhat reduced in the case of high flood waters on account of the effect of back water. The Rock River rises in a marshy region in central Wisconsin, and has a drainage area of approximately 3 250 square miles above Janesville. It is a river of reasonably equable flow, though it is subject to quite low water in the late summer and rather high water in the early spring. Ordinarily it has a very satisfactory flow during those months that afford the greatest daily load for the electric light company.

FIG. 2.—Upper dam and site of present Central plant, during progress of concrete work.

The waterwheel equipment installed at this point consists of six wheels, four rated at 148 h.p. each, and two rated at 100 h.p. each, the four being arranged to drive upon a main horizontal shaft, while the two drive an independent shaft. The latter two are wheels which were already owned by the company when this plant was developed, and they were temporarily installed for use until the demand for power shall become sufficiently great to make it worth while to replace them by wheels corresponding to the other four.

The company had been operating a rather mixed lot of circuits including Edison direct-current three-wire system, 110 volts on a side, for incandescent lamp lighting, with 220-volt direct-current motors between the outside wires; 500-volt railway circuits; alternating-current incandescent electric lighting circuits; direct-current series arc lighting circuits, and circuits to polyphase alternating-current motors. This mixed system had partially come about through the merging of two companies a considerable number of years ago, and partially through the gradual development of the plant toward an alternating-current plant.

FIG. 8.—Upper dam and Central plant.

When the Central plant was constructed and the old plant in the heart of the city abandoned, it was decided that the better economy lay in preserving the mixed system for the present, since considerable of the machinery was in very good shape and a good many direct-current motors were in use. Consequently the company still maintains the direct-current three-wire system, the 500-volt electric railway circuits, and its alternating-current circuits for incandescent lighting and motors. It has changed its arc light system so as to use alternating-current series arc lamps operating from Thomson tub transformers.

Such of the electric generators of the old plant as were modern and in good operating condition were moved to the new Central plant. These included one 500-volt generator for the railway load, two 110-volt generators for direct-current lighting and power load, and a 250-volt direct-current machine which, with other purchased machines, serve a double purpose: namely, either to operate between the outside wires of the direct-current three-wire system, the 110-volt machines, or a compensator, taking care of any lack of balance, or (connected in series with each other) to operate with the 500-volt generator in connection with the railway load. Additional 250-volt direct-current machines have since been purchased and installed for a like purpose.

A synchronous three-phase alternator of 6 600 volts pressure had been in use as a motor driving a jack-shaft in the old city station, receiving power from the Fulton plant, for the purpose of aiding the old city station in coping with its peak-loads. This machine of 85 kw. capacity and another three-phase alternator of 150 kw. capacity were installed in the Central plant, and these are connected to the switchboard in such a manner that they may be used as synchronous motors to receive power from either or both of the other generating plants, thus aiding to drive the generators in the central plant. Likewise, they may be used as generators, being driven by the shaft of the Central plant, and thus deliver power to the polyphase alternating-current circuits and tub transformers. The latter (four in number) are located in this plant and are divided two and two between two phases of the three-phase circuits, while the third phase is connected to the alternating-current incandescent lighting circuits. The three phases are utilized to operate polyphase motors, of which there are several of considerable capacity.

The power house at the central station stands on made ground between the old power canal and the river bank. The foundations are supported on piles. When it came to building the house it was found that a concrete block building could be put up more economically under the particular circumstances than a building of brick and the block construction was therefore chosen, the type of blocks being carefully selected so as to afford a satisfactory appearance. Artificial rock-faced blocks were used in the exterior lower courses and the pilasters of the building, while blocks with imitation bush-hammered faces were used for the remainder of the exterior of the building.

All of the blocks are smooth on the faces exposed in the interior of the building. The roof-trusses are of steel, and the roof is covered with fire-proof roofing. An exterior view of the power house is afforded by Fig. 3. The corrugated-iron extension to be seen in the photograph running toward the observer composes a covering for the wheel settings.

The equipment in use in the power house includes two steam-engines and a boiler which were installed for reserve purposes. The boiler is a water-tube boiler purchased at the time of the erection of the power house and the two engines (respectively a Corliss engine of 300 h.p. and a high-speed engine of 150 h.p.) were moved from the old city power house.

The steam plant is arranged so that the Corliss engine may be connected by friction-clutch to the water-wheel shaft so that the steam and water power can work together.

As the generators in this station are relatively small, they are all belted, and the 110-volt and 250-volt machines are operated in pairs by tandem belts to save space. The low head makes the use of vertical water-wheels necessary, and bevel-gears are used for transmitting the power to the horizontal shaft.

Some engineers who have not had experience in the operation of such plants undoubtedly may criticize the introduction of the small belted units into this plant and the use of tandem belts, but experience shows that it is satisfactory and reliable; and there is no doubt that it has cost the company less per annum through operating these machines than the additional annual charge which would have been imposed by selling these machines at second hand and purchasing others of uniform type. The use of direct connected machines is not practicable under the conditions of the plant.

The Monterey plant which is on the Rock River about two miles south of the Central plant is now operated from the old water-wheels of the cotton mill which are mounted in an unsatisfactory manner, and this summer will see the water-wheel development at this point extended so that the old wheels may be ultimately replaced and the full power of the site taken advantage of. There is also located at this point an admirable Corliss engine of 350 h.p. which was part of the cotton mill equipment, and which is still maintained by the electric company as part of its steam reserve. One 275 kw. three-phase generator is now temporarily installed in this plant, driven by the old wheels of the cotton mill, of which there are four, three being rated at 100 h.p. each, and one being rated at 50 h.p. Additional generating capacity will be added this summer after new concrete penstocks have been put in, and two new water-wheels of 250 h.p. each have been installed therein. The old equipment will probably be maintained for another year to operate in conjunction with the new, after which it will be replaced by larger and better apparatus.

The generating capacity of this plant may be utilized in co-operation with the Central plant, either by operating a synchronous motor at the Central plant to aid in driving the direct-current machinery, or by delivering the alternating currents to the alternating-current distributing system through the Central plant switchboard, or both.

The head which the Monterey dam affords at normal water is approximately 9.5 ft., which is somewhat reduced at times of excessively high water. A fair amount of storage exists in the pond above the dam at each of these plants, namely, the Central and Monterey plants, so that advantageous use may be made of the water for the variable load of the lighting company.

The Fulton plant is about 12 miles northerly from Janesville. It is located on the Yahara River, a stream colloquially known as the Catfish, which is the outlet of a string of lakes which have surface area of about 60 square miles. The stream also has some sources of supply from branch streams entering below the outlet from the lakes. The total drainage area covers approximately 510 square miles above Fulton. The head afforded by the dam is 14 ft. and the pond above the dam affords considerable storage capacity. This plant is therefore used only for peak-loads and is consequently operated only a few hours each day, under ordinary conditions. The plant has been in its present condition for a number of years. Its equipment includes three 75 h.p. water wheels and a 150 kw. three-phase generator. The water-wheels are vertical wheels geared to a horizontal shaft. A small generator is also installed in this power house for the purpose of contributing to the lighting of the town of Edgerton which may be seen on map No. 1. The latter generator is supplied by the owner of the electrical supply for the village of Edgerton, who owns a water power site of very low head on the Rock River at a point marked Indian Ford which can be seen on the map, and who found it desirable to buy some of his power from the Fulton plant of the Janesville company on account of the insufficiency of the Indian Ford plant.

This Fulton plant has a transmission line of 6 600 volts pressure. The city distribution circuits on the alternating-current system are of 2 200 volts pressure. The alternating-current machines in the Monterey and Central plants are of 2 200 volts pressure with the exception of one old synchronous machine which is of 6 600 volts pressure.

Transformers suitably located with respect to this 6 600-volt machine in the Central plant make it possible to use it in connection with the 2-200-volt lines as motor or generator, or to receive power from the 6 600-volt line from Fulton. The same transformers also provide means by which the 6 600-volt line may feed directly into the 2 200-volt distribution circuits.

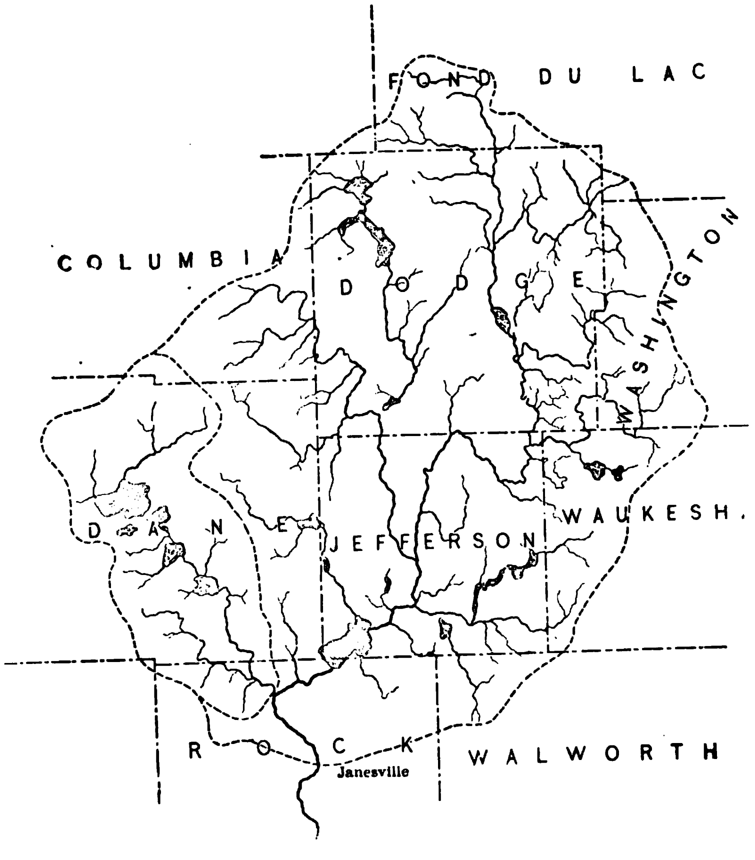
It will thus be seen that the three plants may work together. They ordinarily operate as substantially one generating unit by being associated during peak-loads.

Under usual conditions of operating, the two alternating machines in the Central plant are utilized as motors in driving the direct-current machines, deriving their power from the other two stations, and the alternating-current distribution lines of the system are supplied by current from the other two plants through the Central plant switchboard. The arrangement of the switchboard is simple but it affords the possibility of operating the plants in any combination on the distribution circuits, either with each other or singly, as the storage of water or other conditions may make desirable. A thoroughly efficient combination of the three plants is accomplished, and the company is remarkably well fortified against interruptions of service.

The synchronous alternating-current machine, being operative either as a generator or motor without any changes in its connections, is a device of great convenience in a system like that of the Janesville Electric Company. It also adds materially to the reserve generating capacity of the plant so that some economy of space results, and some driving gear and machinery is dispensed with.

The map No. 3 shows that the drainage area of the Rock River above Janesville includes nearly the whole of the counties of Dane, Jefferson, and Dodge, and considerable portions of the counties of Rock, Waukesha, Washington, and Fond du Lac, most of which are notably excellent and well cultivated farm and dairy counties. This gives a reasonable basis for expecting fairly stable conditions of the water power, so that the future power may be reasonably estimated from the records of the past.

The map illustrates in a rather graphic manner the general characteristics of the drainage area with its numerous lakes and streams. The river has an average slope of about 1.2 ft. to the mile and runs through a country of loamy soil which was once covered by extensive forests that have now disappeared, and the land is well developed for agricultural purposes. The area lies in the region of glacial drift which accounts for numerous lakes and marshes and their tributary small streams. The extreme source of the river is the extended Horicon marsh,



MAP No. 3.—Drainage area of the Rock River above Janesville.
Scale, 1 in. = 10 miles.

once a large lake, but now partially drained. The river is fed as it flows southward by numerous streams which usually themselves originate in small lakes and marshes, and it passes through Lake Koshkonong, widely famous as a feeding ground for canvas-back ducks during their migrations. About a dozen miles from Janesville the river receives the waters of the Yahara which discharge from the Four Lakes of Madison and from various small streams and marshes.

The Fulton plant is located on the Yahara River above its junction with the Rock River.

A peculiarity of the under soil of the area robs the river at Janesville of that uniformity of flow throughout the months of each year which might be expected from the considerable area of lakes and marshes which contribute to the waters of the river. A substratum of sand and gravel or sandy nature lies beneath the surface soil and carries a heavy flow of underground water throughout the year. It may be reasonably supposed that a goodly proportion of the total waters discharged from the area are found in this underground flow and that the apparent river flow suffers most of the fluctuations following precipitation, thus causing an increased ratio between the waters discharged by the river in the high- and low-water months of each year.

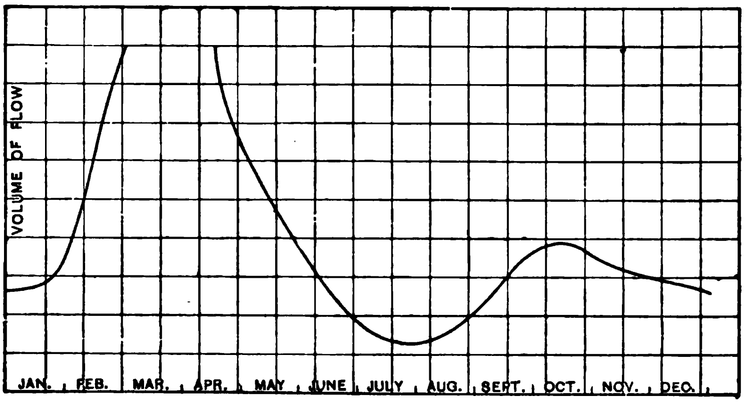


FIG. 4.—General character of variations of stages of water throughout the year.

The gaugings of the Rock River do not extend as far into the past as could be wished, and those records that exist are meager and were mostly taken at stations below Janesville, but the drainage area extending to one of those stations is of the same general character as the area above Janesville, and estimates of the Janesville flow must be based on those gaugings. It seems on this basis, that the Janesville Electric Co., after raising its dam at Fulton a little, can afford to install water-wheels with a capacity, as a probable ultimate limit of 2 500 h.p. to meet the requirements of increasing loads. Four fifths of this capacity would be about equally divided between the Central and Monterey plants and the remainder would be located at Fulton. This equipment would be made with the expectation of taking the utmost advantage of the storage ponds at the dams for the purpose of helping over peak-loads which demand more power than the normal flow of the river at the time, but do not exceed the capacity of the water-wheel installation. When the load has grown to make this water-wheel capacity needed, it may be expected to operate as much as five hundred or six hundred horse power of the steam reserve for several hours per day during the months of November and December, and small amounts of steam power will likely be required for short times during some days in other months,—such as the months of August and September when the flow of the river is ordinarily at a minimum, or the months of March or April for the days of excessively high water accompanied by decreased head caused by back water. Fortunately the flow curve of the river has its lowest position in months when experience

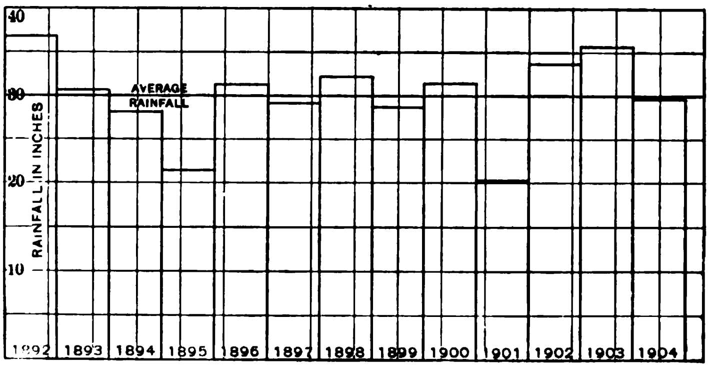


FIG. 5.—Annual rainfall on drainage area of Rock River, averaged from records taken at eleven stations.

shows that the demand for electrical energy is likely to be relatively small, and the total use of steam power for the year may be decidedly small.

Fig. 4 shows the general slope of the flow curve of the river during a year. This is merely typical, and is introduced to indicate the months of the year when the low and high water may be expected. The actual flow curve of the river has many sinuosities not shown.

Rain fall records taken within the drainage area of the Rock River do not extend far enough into past years to be very serviceable as an aid to estimating the stability of the water power considered for a cycle of years, but Fig. 5 shows the annual rainfall averaged for 11 stations on the drainage area and extending back for 14 years. Fig. 6 shows the annual rainfall as observed for 50 years past at the cities of Beloit and Milwaukee. Beloit is located on the Rock River some 14 miles below Janesville. Milwaukee is located directly on the shore of Lake Michigan, some 80 miles east of Janesville and a few miles east of the eastern boundary of the Rock River water shed. The effect of the environment of Milwaukee makes its rainfall records of little use for consideration in connection with the Rock River area.

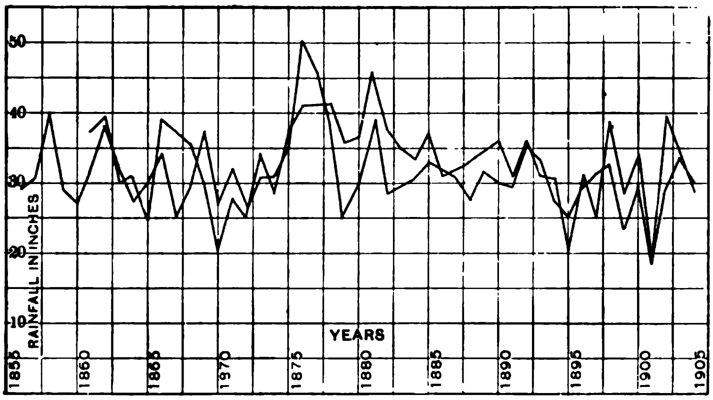


Fig. 6.—Records of rainfall at Beloit and Milwaukee.
Full line, Beloit; broken line, Milwaukee.

The Janesville Electric Company has made remarkable progress under efficient management. During the year 1905 the electrical output aggregated nearly 2 000 000 kw-hr. which was absorbed by a city of 15 000 inhabitants. The corresponding output for the year 1903 was little exceeding one half as great. During the year 1905, which was the first year in which the full advantage of the water power at the Central plant was available, there were only five days during which the steam reserve was operated on account of lack of water power; these were the first five days of April when the water reached a height greater than had been recorded in the previous 20 years. During these days, three fourths of the Fulton output was sent to Edgerton because the power of the low head Indian Ford dam was wiped out by the high water, and the Edgerton supply had to be purchased from the Fulton plant, though ordinarily the Fulton plant only furnishes power to Edgerton in the winter time, to help out with the peak load between five and six o'clock. During the early part of the year 1905 a steam driven generator was operated in connection with the street railway service, but this was due to the fact that the generating capacity had not been fully installed. During the very last part of the year, the same condition arose on account of the growth of the output, and a steam-driven generator was connected on the street railway service nearly every evening for a short time, but this condition will be helped after the pending Monterey improvements have been completed this summer.

The saving in the cost of fuel over operating a steam-driven station is sufficient of itself to make a good return for the extra cost of the power development.

The plants are also fairly economical from the standpoint of the labor required, considering the division between three sites. The Fulton plant, which operates upon peak loads, is operated and cared for by one man who lives in the vicinity of the plant. When important repairs are required, men are sent from Janesville, but otherwise this one man furnishes all required labor. The Monterey plant is operated for the 24 hours by two men, one man on each 12-hour shift. The Central plant is operated by four men, two men on each 12-hour shift. Thus the three stations require a total of 7 operating attendants on the pay roll, whose labor is distributed during the 24 hours. These men have the care of substantially 1 200 kw. in generating capacity beside tub transformers, water-wheels, steam reserves, etc. If the plants were combined in a single steam-driven station furnishing the same variety of service, such a station would probably require an aggregate of more than seven operating attendants on the pay roll.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

SOME FUNDAMENTAL CHARACTERISTICS OF MERCURY VAPOR APPARATUS.

BY PERCY H. THOMAS.

INTRODUCTORY.

The characteristic of the type of mercury vacuum apparatus, invented and developed by Mr. Peter Cooper Hewitt, which distinguishes it most clearly from other forms of vacuum tubes, is its power of passing a comparatively large continuous current with a constant and comparatively insignificant voltage loss. There are, of course, other important features of this mercury vapor apparatus characteristic to it, such as the negative electrode starting resistance; the disintegrating, reconstructing negative electrode, etc.

It is the object of the present paper to discuss a number of the more prominent fundamental characteristics of mercury vapor apparatus, and their reactions on the related electric circuits; and further to suggest a conception of the nature of these phenomena which shall be consistent with the latest theory of electricity. A certain amount of repetition of information already published will be unavoidable.

ELECTRICAL CHARACTERISTICS OF THE CURRENT PATH IN THE VACUUM.

Current passing through the vacuum space in the mercury vapor apparatus experiences a loss of voltage, the numerical value of which tends to remain constant independent of the current strength, except with small currents; for example, currents less than one or two amperes. Although this voltage loss, or drop, is practically independent of the current strength, it still is not of the nature of the counter electromotive force of a storage-battery or motor, which latter are capable of delivering current in a reverse direction on the removal of the supply electromotive force. Neither is it equivalent to an ohmic resistance, for it is of an entirely different nature. It cannot be properly spoken of as a resistance at all; it is a voltage loss.

This loss is the sum of three other losses, more or less different in character; that is, the vapor loss, the positive electrode loss, and negative electrode losses.

Vapor. 1. The voltage loss in the vapor increases with increase of vapor pressure, and more or less closely in proportion to this pressure; consequently, since the mercury vapor is saturated and its pressure depends directly upon the temperature of the mercury electrode, the vapor voltage loss is more or less proportional also to the temperature of the mercury electrode or electrodes.

2. The voltage loss depends upon the chemical composition of the vapor; that is, it will be different with oxygen, hydrogen, and air, even at the same pressure; and all of these give a much greater loss than mercury, which is one of the great advantages in the use of the latter.

3. The voltage loss is directly proportional to the length of the vapor.

4. The voltage loss is inversely proportional to the diameter of the vapor path, but not, as might be supposed, inversely as the area of the path.

5. The voltage loss is nearly independent of the current strength, but varies slightly in a direction opposite to the current. The curves of Fig. 1 show the change of voltage with change of current, and are characteristic respectively of the voltage across a 3.5-ampere commercial lamp and 30-ampere commercial converter bulb. These curves show directly the total voltage across the apparatus, but virtually represent the resistance of the vapor, plus a constant loss of perhaps 10 volts at the electrodes.

Positive Electrode: The loss of voltage which occurs at the positive electrode is practically independent of the current strength. The energy represented by this voltage appears as heat at the surface of the electrode. The material of the solid positive electrode seems to have no appreciable direct effect on the volts lost, but a mercury positive, except when perfectly cold, has a loss some volts higher than the solid, probably because of a layer of comparatively dense vapor produced at its surface by the current. This is usually to the disadvantage of the mercury electrode. As the watts energy liberated in the form of heat at the positive electrodes in a commercial apparatus may be quite considerable, the solid positive electrodes have a further advantage over mercury in that they will become heated during operation, and radiate a considerable portion of the heat developed on them, as heat is radiated from a hot coal. This puts no burden on the cooling power of the bulb itself, while mercury positive electrodes will be kept cool by the evaporation of the mercury and additional vapor must be condensed by the bulb. The voltage loss on the positive electrodes is usually found to vary a good deal, but not on account of current variation. Its minimum value is about 5 volts. Apparently on account of an accumulation at this electrode of a certain amount of some foreign gas, such as air, which has already been stated to have a higher resistance than mercury vapor, the positive electrode loss appears often more than 5 volts. The loss is practically independent of the temperature of a solid positive electrode.

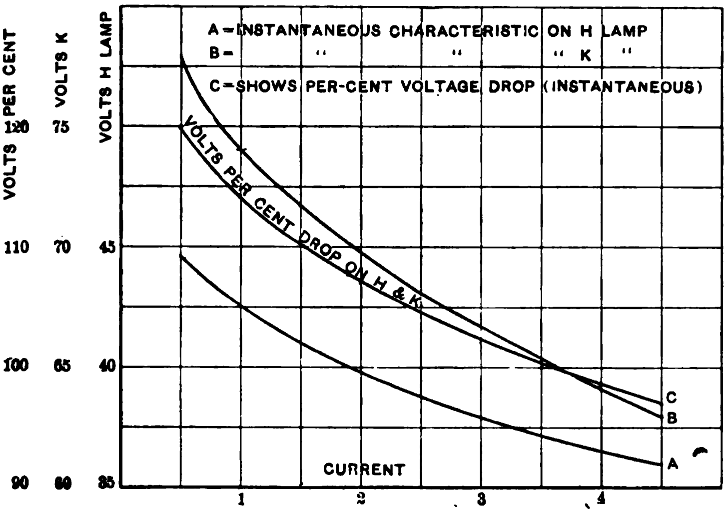


FIG. 1

Negative Electrode: During normal operation there is also a voltage loss at the negative electrode, practically independent of the current. In a mercury electrode this loss is probably about 4 volts. It is practically independent of temperature and physical form.

This loss of voltage *during operation* must be distinguished from the resistance to starting, residing at the negative electrode and usually called the negative electrode starting resistance, or, more briefly, the negative electrode resistance.

The current enters the negative electrode through a very clearly defined small, bright area, or " spot," even on very large electrodes, which normally flits about rapidly over the whole surface when not subjected to the influence of a magnetic field. When, however, a magnet is brought into the neighborhood, the electrode spot is driven to one side as far as the edge of the electrode. By providing an amalgamated metallic body at the surface of the electrode, the negative electrode spot may be caused, under some conditions, to rest quietly on the surface at the junction of the mercury and the solid material.

The negative electrode spot causes a violent agitation on the surface of the mercury and acts as though it exerted a pressure downward, making a depression on the surface. There is, at the same time, a very rapid evaporation of mercury at this point, which seems to be an essential part of the transfer of the current from the vacuum space to the electrode proper. At the same time that the negative spot is vaporizing mercury, it is also heating the electrode itself, which finally becomes so hot as to cause further vaporization. The evaporated mercury is cooled and condensed by contact with the bulb, on the inside of which it collects in drops. The drops grow larger and finally run down into the electrode, tending to cool it.

Thus by the passage of current, the negative electrode is heated and mercury evaporated—and further the vapor itself and the + electrode are heated. Since the coolest surface in contact with the vapor is the bulb, the vapor condenses on its surface, so that the heat which was abstracted from the mercury electrode by evaporation is delivered to the bulb by condensation. There is in addition some heat radiated directly from the + electrode when this is of solid material. As there is a best pressure for the mercury vapor in the operation of the apparatus, it is evident that there must be a definite relation between the heat generated and the heat radiated or dissipated by the bulb. In mercury vapor lamps this fact leads to the use of the so-called "condensing chamber," for the light-giving tube alone has not, in the sizes used in practice, sufficient cooling surface and, furthermore, it is preferable that the condensation shall not occur where it can obstruct the passage of light. In converters the main object is to get as much cooling surface as possible with the shortest practicable vapor path.

The operating negative electrode when the current does not exceed 3 or 4 amperes, and the temperature is comparatively low, has a remarkable characteristic in that it experiences at irregular intervals an extremely sudden and abrupt return of the negative electrode starting resistance. This may occur in any degree of severity and at any instant. The tendency, however, lasts but for the briefest instant of time and has little or no effect on an ammeter measuring the current in the apparatus. As could be expected in view of this behavior, it is desirable to provide a mercury vapor apparatus using small currents, such for example as the 3.5-ampere lamp, with special means for overpowering this momentary increase of resistance. The well known choke-coil (properly called a sustaining coil) used in connection with Mr. Hewitt's lamps, serves this purpose. It is evident that when once the current has been established in the coil, any action tending to stop the current is resisted by the energy stored in the coil, so that by making the coil large enough, this resistance, which exists only the briefest instant of time, will be entirely overcome. This tendency practically disappears with currents over 4 or 5 amperes, and also when the negative electrode is very hot. It is most severe on a cold negative and on a small current. With one ampere on a cold negative it is very difficult to secure steady operation of the negative electrode. This tendency is, to a certain extent, cumulative; that is to say, a certain choke-coil will run the lamp a few seconds, a large coil a few minutes, a still larger coil an hour, while perhaps a still larger coil will be necessary for continuous operation. It occurs absolutely independently of any variation in the supply voltage.

Its most unexpected feature is its extreme abruptness, probably at least of the order of $\frac{1}{100\,000}$ part of a second. Of course, only choke-coils with open magnetic circuits can respond quickly enough to be of service in counteracting this impulse. As a natural result of the extreme abruptness of this action, it has been found that even a very slight electrostatic capacity, such as the capacity between a twisted pair of insulated wires 10 ft. long, has a great weakening action on the coil if connected between it and the negative electrode. This result seems out of proportion to the value of the energy stored in the capacity to the energy stored in the choke-coil. Presumably the brief instant required for the instantaneous charging of this small capacity which must be accomplished before the choke-coil can supply voltage to the electrode, is sufficient to allow the negative electrode resistance to be established.

STARTING CHARACTERISTICS.

A voltage considerably higher than the normal operating voltage may be required for starting the flow of current through the vacuum. For a tube of definite diameter the difference between the starting and the operating voltages is very small for short lengths of tube, perhaps up to 10 diameters. But the operating voltage increases directly as the length, while the starting voltage increases more nearly as the third power of the length, so that for long tubes there is a very considerable increase of voltage required for starting. On the other hand, the starting voltage is lessened by increasing the diameter of the tube. This high .starting voltage is partly due to the necessity of establishing a path through the opposing gas, and to vapor molecules initially filling the whole space. Once such a path has been established with a considerable volume of current, a much less voltage will evidently keep it clear. In many types of apparatus it is found convenient to start on an auxiliary positive electrode placed near the negative and transfer the current to the main positive electrode after starting. In this case the starting resistance of the vapor path to the main positive electrode must be overcome before normal operation can be established. In a converter bulb where the distance between the negative and the positive electrodes is comparatively short, no greatly increased voltage is required for starting the current through the vapor path proper. In a lamp tube 45 in. long and 1 in. in diameter, such as is used in one type of commercial lamp, several times the operating voltage may be required for starting the current through the vapor, independent of the negative electrode starting resistance. A high resistance filament connected to the + electrode and extending into the neighborhood of the negative will reduce this vapor starting resistance by allowing the current to climb up, so to speak.

Positive Electrode: There appears to be no resistance to starting at the positive electrode other than the normal operating resistance.

Negative Electrode: The negative electrode starting resistance is too well known to need further description. There are two well known methods of overcoming this starting resistance:

1. By establishing a current through a complete metallic circuit within the vacuum, and breaking this circuit within the vacuum, in which case the original current will continue to flow, since the negative electrode resistance never has a chance to assert itself. This result may be accomplished by having two mercury electrodes which may be brought into contact by tilting the container, or otherwise, or by moving suitable parts from outside by a magnet. This type of starting is one of the most commonly used at the present time.

2. The second method of starting consists in directly applying a high potential with or without the addition of various means for reducing the starting resistance.

This negative electrode starting resistance is a very variable quantity and ranges from almost nothing to many thousand volts, according to conditions. It is very much greater with a cold electrode, especially a cold mercury electrode. It is dependent upon the form and surroundings of such an electrode, and especially upon the potential or charges on the outside and inside of the insulating walls which confine the electrode. If the negative electrode, as shown in Fig. 3, is provided with a metallic strip, called a starting band, outside the container, and this strip be charged at a potential different from the electrode, the starting resistance is weakened or may be entirely overcome. On the other hand if this band or strip be connected to the negative electrode itself, the negative electrode resistance is rendered more stable since it is protected from charges. This is the principle made use of by Mr. Hewitt in starting some of his lamps, and has been already fully described by him. The connections are shown in Fig. 2. In this figure the interruption of the current in the quick-break switch *S* causes a momentary high potential impulse from the choke-coil *I*, which is applied. both to the starting band in the neighborhood of the negative electrode and to the main positive electrode. The former serves to break down the starting resistance of the negative electrode, and the latter supplies the starting voltage for the vapor path. In this method of starting, a small spark or series of sparks can be seen jumping from the edge of the negative electrode to the inside surface of the glass opposite to the starting band, which surface forms the inside coating of a small condenser, the starting band being the outside coating. This small spark is undoubtedly what overcomes the negative electrode resistance.

Physical Nature of Vapor Conduction.

It is interesting to speculate as to the nature of the phenomena connected with mercury vapor apparatus, and to endeavor to discover some assumption upon which they can be explained, which shall also be consistent with the best hypothesis as to the nature of electricity. The writer has gradually arrived at a way of looking at these things which explains nearly all of them quite satisfactorily, and it is here described for what it may be worth, with the distinct understanding

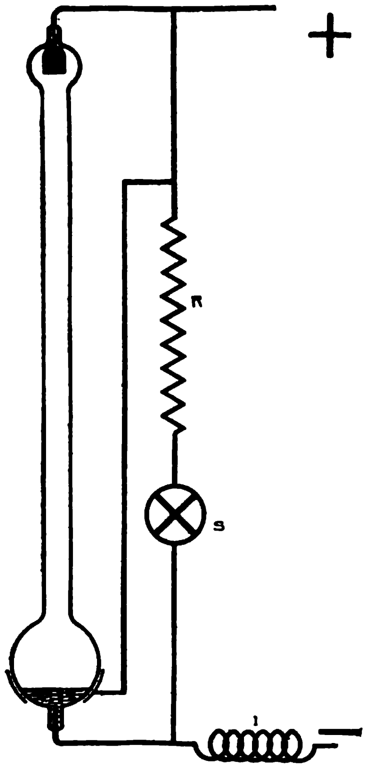


Fig. 2. Circuit for high-tension starting of direct-current lamps. *R* is ohmic resistance. *S* is a quick-break switch *I* is inductance.

that it is merely a tentative theory until a sufficiently complete body of information shall be available to prove or disprove it.

We may assume that by electricity is meant a greater or less number of those small particles, described by J. J. Thomson as having a mass of about $\frac{1}{1000}$ part of the hydrogen atom, called electrons. A current of electricity, then, is nothing but a stream of these electrons. Since they move in a direction opposite to the conventional current direction, they are said to carry a negative charge; whether the electrons are electricity or carry charges of electricity is immaterial in this case. When we have a direct current passing through mercury vapor apparatus, we have a continuous stream of electrons passing from the negative to the positive electrode within the vacuum and returning through the external circuit, which must include a source of electromotive force. These electrons are caused to move by the electromotive force of the circuit, which causes an increase of potential (that is, a deficiency of electrons) at the positive and a decrease of potential (that is, a surplus of electrons) at the negative; or, to put it another way, a static charge is produced on the positive electrode which attracts the electrons, while they are, of course, repelled from a negative charge on the negative electrode. The moving electron, like a moving electric charge, stores energy electromagnetically; that is, has inertia.

These electrons are invisible of themselves and pass with extreme velocity, naturally in straight lines and where unrestrained tend to spread apart and fill the whole vapor path.

In a mercury vapor apparatus the voltage loss in the vapor itself is supposed to be due largely to the presence of molecules or atoms of gas in the path of the electrons which impede their free motion. Since the greater the number of gas molecules in a given space the greater the pressure, it is natural to suppose that increase of pressure would mean increase of resistance to the electrons. Furthermore these gas atoms or molecules are agitated and set in vibration in being struck by electrons and are caused to give off both light and heat. The light naturally will be the spectrum light of these particular atoms; that is, the particular color or colors corresponding to the natural period of vibration of this particular kind of atom.

When the pressure is sufficiently high, the electrons, instead of spreading through the whole space are forced into a narrow stream in the center, and the obstructing molecules are at least partly forced to the outside, to be spectators as it were. This effect can be very easily seen by heating the condensing chamber of a mercury vapor lamp with a flame until the vapor reaches a comparatively high pressure, the current will then " string "; that is, will be confined to a brilliant, thin, sinuous line near the center of the tube.

The varying specific resistances of different gases is easily explained by the differences in the character of the molecules.

The negative electrode is assumed to be the source of the electrons which enter the vapor, and the phenomenon of the negative electrode starting resistance is easily explained; that is, if we imagine the small electrons to be material particles, a considerable force would be required to cause them to break out from inside the liquid mercury surface on account of its surface tension, while when once the flow is established on a large current, it is easy to imagine that either on account of the extreme local heating at the surface of the negative electrode, or the rapid evaporation of mercury into vapor at the negative spot, there should be no opportunity for the formation of a new surface on the mercury which could re-establish the electrode resistance. On the other hand, with small currents it is found that the surface tension is able to reestablish itself in spite of the current, so that with currents of intermediate values it would be expected that at intervals the mercury would be able to reestablish the normal surface when accidentally the conditions should be favorable. Hence the advantage of employing a sustaining coil in connection with apparatus using small currents. The lessening of the negative electrode starting resistance, and the lessening of the importance of the sustaining coil with the heating of the electrode correspond properly with the corresponding reduction in surface tension.

The normal operating voltage loss at the negative must be connected with the separation of the electron from the mercury atom and the evaporation of mercury.

According to the assumption, it should be noticed that the source of electrons is not the ionization of the *gas* or *vapor* within the container as in many other experiments—such as the passing of current through air ionized by X-rays—but is the negative electrode itself; that is, within the vapor space during the flow of current we should find normally no *positive ions* (which are to be taken as atoms or groups of atoms which have been deprived of one or more electrons), only the electrons drawn out of the negative electrode. Thus it would be possible to pass current through the apparatus, even were it to have a perfect vacuum within. Although the *resistance to starting* in an apparatus in this condition is very high on account of the extreme surface tension, and on account of the absence of positive ions (as more fully explained in a later paragraph), yet once the apparatus is started, the passage of current is exceptionally easy and no light is obtained. It is actually found that with cold mercury electrodes no light appears with currents of over 100 amperes. This is a very interesting point, as it has commonly been supposed that a perfect vacuum is a non-conductor; whereas the truth probably is merely that a perfect vacuum has an extremely high starting resistance, but is a most perfect conductor once current has been established.

The question naturally arises: why the negative electrode resistance does not exist in connection with arcs between electrodes in air at atmospheric pressure? It is possible that the following is the proper explanation: the application of a sufficiently high potential previous to the breaking down of the gap upon a spark-gap in air causes an ionization of the air between the electrodes, the negative electrons being attracted to the positive electrode, and the positive ions to the negative electrode. The negative electrons, of course, enter the positive electrode without difficulty, while the positive ions are stopped at the surface of the negative electrode on account of the negative electrode resistance, and attract electrons from within the metal of this electrode up to the surface. We then have positive and negative charges attracting each other, and separated merely by the surface of this electrode, which causes a tremendous strain and is sufficient to withdraw electrons from the negative electrode to neutralize the positive ions, thus breaking down the negative electrode resistance. According to this theory (there being no ionization of vapor), no positive ions will be formed in the mercury vapor apparatus and no such strain produced on the negative electrode; in other words, the vacuum causes the withdrawal of the positive charge (which tends to start the negative) from the surface of the negative as in the air to the positive electrode with a vacuum; thus very much reducing the strain produced on the negative. Hence the mercury vapor acts as though it could not be ionized in the same sense as oxygen or nitrogen, which is more or less natural in view of the monatomic nature of mercury vapor, especially at vacuum pressures. This theory beautifully explains the " softening " of X-ray tubes by the production within the vacuum space of a slight amount of gas, which becoming ionized renders the cathode more easily broken down.

X-ray tubes, Crooke's tubes, and similar vacuum apparatus cannot operate as the vapor electric apparatus of Mr. Hewitt, for two reasons:

1. Because they are not operated with a supply capable of furnishing enough energy to break down completely the negative electrode resistance and reduce it to a normal running value; and 2, because they are so physically constituted as to destroy themselves if operated with supply apparatus of sufficient energy for operating Cooper Hewitt apparatus.

It should be noted that within the vacuum space of a mercury vapor apparatus are two streams of material; electrons passing from the negative to the positive electrode, and the atoms of mercury vapor passing from the negative electrode spot and other hot mercury surfaces to the cooler parts of the container, where they condense. Both of these streams of particles, though so radically different in character, have the power of sweeping with them atoms and molecules of any gas which may be found within the vacuum space; *i.e.*, any such residual gas tends to collect at the positive electrode, or at the condensing surface of the retainer. In the latter location it is very readily absorbed by the condensing mercury, which explains the fact that some apparatus, originally in slightly imperfect condition, will improve with actual operation. At the positive electrode, however, if sufficient in quantity, this accumulated gas will usually raise the voltage of the apparatus on account of its intrinsically high specific resistance, and may also cause an excessive heating of the electrode.

On account of the general acceptance of the hypothesis that electricity is constituted of or connected with electrons which pass from the negative electrode to the positive electrode in the vapor path, it has been proposed to reverse the convention as to direction of the electric current adopted long ago, before any marked difference between positive and negative had been discovered; viz., the convention that *current* runs from the carbon to the zinc element of a battery in the external circuit.

We then should say that a positive current is one which passes from the mercury electrode of a vapor lamp to the iron electrode, and an electron would carry a positive charge or be a positive charge according to the particular assumption as to the nature of electricity which might be accepted. Such a change would certainly be highly desirable, except for the great probability of confusion for some time afterward.

MERCURY VAPOR LAMP.

As a lamp, the mercury vapor apparatus has a number of interesting characteristics. Its great efficiency, which in long tubes reaches ½ watt per c.p. (exclusive of resistance losses), is obtained only when run under the most favorable conditions; for example, only with the proper vapor pressure, current, and tube diameter. Mercury vapor is a much more efficient material for light production than most other gases and vapors whether used alone or mixed. The addition of atmospheric air, for example, to mercury vapor, even in very small quantities, increases the voltage on the tube very much, thus increasing the energy supplied.

The spectrum of mercury vapor is, furthermore, one of the most complete and usable gas spectra; it contains a variety of colors in substantially equal proportions, chiefly an orange-yellow, a yellow, a blue and a violet, with a smaller amount of a green-blue. The only portion of the spectrum not pretty well represented is the red, which, generally speaking, is the least desirable color. The mercury spectrum has proved to be excellent physiologically, and extremely well adapted to most mechanical processes. It is possible of course by the addition of other gases to add red to the spectrum, which may then be quite prominent, especially if means are taken to condense a portion of the mercury vapor. In general, however, these combinations of gases are more or less likely to deterioration and alteration, and have a considerably lower efficiency than pure mercury vapor. For most purposes the color would not be more desirable with the addition of red.

Light Efficiency: The efficiency of mercury vapor as a source of light follows a number of laws. 1, the watts per candle-power vary with the pressure of the vapor, having a minimum at a certain pressure, as shown in Fig. 3, which is from a test on a commercial type of lamp. 2, it is nearly independent of the current strength within certain limits, in this case it being assumed that the pressure, temperature, etc., are constant.

3. Superheating the tube, and consequently that portion of the vapor emitting light, seems to have little effect.

It will be seen by the curves in Fig. 3, on which is shown the normal lamp voltage characteristic, that is, the relation between current and voltage of the operating lamp, that the most efficient light giving point is at, or nearly at, the point of lowest voltage on this characteristic. This is fortunate, since for purposes of regulation this is a most desirable point to operate the lamp. Above this most efficient point the pressure of the mercury vapor increases rapidly, and while also increasing the candle-power it increases the voltage in the tube in still higher proportion. Below this point the voltage on the lamp rises, probably partly on account of traces of residual gas not exhausted in the pumping, which causes a great dropping off of the quantity of light and the efficiency. These residual gases are here more prominent on account of the lower mercury temperature and vapor pressure.

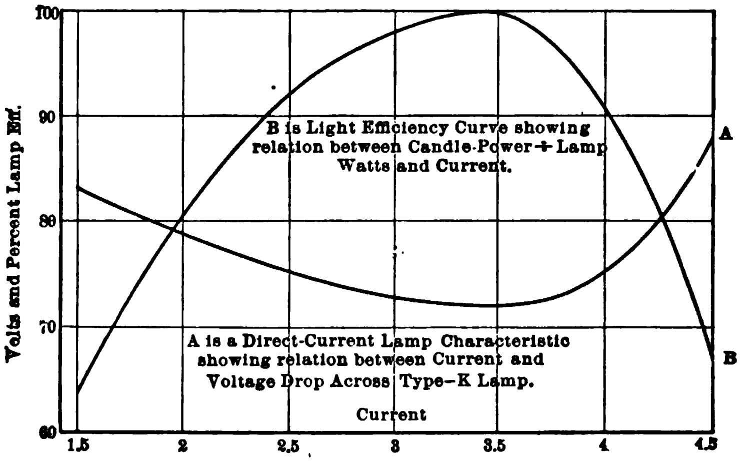


Fig. 3.

It is evident that the temperature of the mercury electrode and the pressure of the mercury vapor resulting from a given current will depend directly upon the air temperature surrounding the lamp. In the commercial types of lamp, however, the actual change in efficiency from change in atmospheric temperature is very slight throughout the practical working range. This results from the flat form of the lamp characteristic near the point of 3.5 amperes, as seen in Fig. 1.

Lamps may be made for various uses with different diameters of light-giving tubes. The diameter most commonly used and suited to 3.5 amperes is 1 in., or a trifle less, in inside diameter. To give the same intrinsic intensity with other diameters the current should be varied in proportion to the cross section of the tube; that is, for a 2-in. tube we should require about 14 amperes. Since the voltage decreases as the diameter of the tube, and since at the same intrinsic brilliancy the quantity of light increases as the diameter on account of the larger surface, we should expect double the light and double the energy consumed with the larger tube. It is found by measurement, however, that the larger tubes are somewhat more efficient, so that there is a saving of 20 to 25% on the efficiency for 2-in. over that of 1-in. tubes—inversely with smaller tubes and the appropriate currents. With smaller tubes, however, the difficulty of maintaining the negative alive becomes very much greater on account of the small current which, as already explained, is subject to momentary impulses tending to stop the flow of current.

There can be no one proper method of measuring the candle power of a Cooper Hewitt lamp; first, on account of the fact that the color of the lamp is different from the color of any accepted standard, and because it is a spectral against a continuous spectrum; and secondly, because the light-giving tube is not a point, and the law of inverse squares does not hold except at very great distances. For commercial tests the candle power of the lamp should not be measured at a great distance, since the lamp has a practical advantage over most other lights from its tubular form, which comparative advantage it would lose were the candle-power measured at a considerable distance. Where it is important actually to define the candle power of these lamps, the particular method of measurement to be used must be specified.

Alternating-Current Lamp: The principle of the alternating-current lamp is generally well understood by this time, the circuits being shown in Fig. 4. Referring to this figure it is evident that during one alternation, current is supplied from one half of the transformer secondary through the lamp tube back to the neutral point, and during the other alternation by the other half of the transformer secondary through the tube to the same point, and that the choke-coil in the negative lags the current over the zero points.

The light from the alternating-current lamp is practically equivalent to that from the direct current, since in the light-giving portion of the tube the light is substantially direct current.

On 25 cycles, by providing a larger choke-coil in the negative than is necessary in the 60-cycle lamp, the natural tendency to flicker with the period of the 25 cycles is eliminated.

Starting: The method of starting in the type-C alternating-current lamp is an extension of that of the direct-current lamp and is of some interest. A small electrode or pin is placed in the head of the lamp as shown in Fig. 4, and connected to one of the positives through a rather high ohmic resistance. In starting, the lamp is tilted so that the mercury forms a continuous stream from the negative to the positive end and is carried by its momentum up around the inside end of the tube until it touches the pin which is placed on the top side of the tube. On account of the irregularity of the flow of the mercury it here makes and breaks contact with the pin a number of times, each time causing a breakdown of the negative electrode resistance, either on the column of mercury or the pin. In the latter case the lamp will go out at the end of the alternation. If, however, the mechanical break at the pin occurs during such an alternation that the mercury column is the negative the lamp will start to operate upon the pin, and that main positive electrode to which the pin is not connected as positive electrodes and the mercury stream as the negative. Then, on account of the starting resistance connected with the

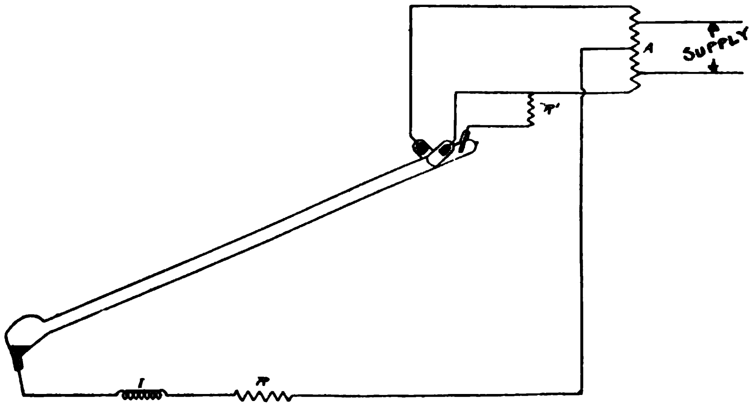


FIG. 4.—Starting and operating circuits for type-C, alternating-current lamp.
A is an autotransformer. *R'* is a starting resistance. *R* is lamp resistance. *I* is inductance.

pin, the current will be immediately transferred from it to the corresponding positive, and the lamp is started. The lamp is then returned to its normal position and all the mercury flows back to the negative. If, now, there were no resistance between the pin and its positive electrode, and assuming the lamp to have been started during tilting by one of the breaks between the mercury and the pin, it is evident that if the mercury touches the pin again, that the lamp will go out, since for this instant the flow of current does not enter the vapor at all (on account of the metallic connection between negative and one positive). That is to say, if it were not for this resistance which prevents current when once transferred to both main positives from being withdrawn by a subsequent connection between the mercury and the pin, the lamp would be started and put out and started again repeatedly. Only the last break between the mercury and the pin would count in starting, and we should fail to light the lamp more often than we succeed. As an actual matter of fact, lamps have been built which started practically every tilt, though the average commercial lamp is not expected always to light at the first trial.

MERCURY VAPOR CONVERTER.

The Cooper Hewitt apparatus may, as is well known, be utilized to supply direct current from an alternating current supply by virtue of the negative electrode resistance. No further description of the general method of accomplishing this result is necessary at this time. The converter may be run single phase, in which case a connection similar to that already described in Fig. 4, except for starting circuits, is generally used, though it may be three-phase, four phase, etc., in which case no choke-coil in the direct-current circuit is usually required.

Starting: In a converter a very short vapor path is purposely provided, and the starting is easily accomplished by breaking a metal circuit in the vacuum as already described, for the current is here easily transferred from the starting to the main positive electrode. The method can be easily seen from Fig. 5, which shows a form of commercial bulb used for a single-phase converter together with starting circuits. There are two electrodes of mercury, one being the main negative and the other a starting electrode. By shaking these two together, passing current through and separating them, the negative electrode resistance is broken down and the voltage upon the main positive electrodes forces current to flow to the main negative. The supplementary positive should then be cut out of the circuit. Converters, however, can be started by starting-band and high-tension impulse, or by the direct application of sufficiently high potential.

In cases where the converter is to feed a storage-battery, it will be noted that the electrical connection shown in Fig. 4 for the alternating-current lamp is not perfectly satisfactory, on account of the comparatively large direct current sent by the battery through the transformer winding when the negative and starting electrodes are connected, which is in the wrong direction to start the negative electrode as a negative. The high impedance of the sustaining coil prevents any considerable alternating current from flowing, but does not seriously limit the flow of direct current from the battery, which thus tends to make the starting positive a negative. The difficulty may be avoided by the method shown in Fig. 5. By this method the battery is made to start the supplementary electrode as a negative, whereupon the main positives start operation with the supplementary as a negative, passing current through both the resistance *R* and the battery, through the coil *T*. If then a second connection is made between the starting and the main negative electrode; the current is shunted from the coil *T* through the main negative, and on the second separation the main negative starts in the proper direction, as current is now passing against the battery instead of from it. On account of the liquid character of the mercury, it is found by experience that with one tilting operation two " makes " and " breaks " are ordinarily produced between the main and starting electrode, so that the initial starting on the supplementary electrode and the transfer to the main negative occur almost together so as not to be distinguishable by the eye. The starting circuit should usually be cut out during regular operation. By making the coil *T*, a magnet for tilting the bulb, the starting is automatic. This method has an advantage over other apparatus for automatic starting in that it is not necessary to operate any switches in the main circuit carrying the heavy current; the only cut-out that is necessary is the disconnection of the starting circuit which carries at most one or two amperes.

Converter Bulbs: There are very few new fundamental features or conditions introduced into the mercury vapor apparatus in its use as a converter. One characteristic, however, deserves mention; there is a tendency, under certain conditions, for the negative electrode resistance of a positive electrode to fail, which causes current to flow from some other positive directly to the positive in question, causing practically a direct short-circuit on the system. By proper design this tendency can be controlled very effectively.

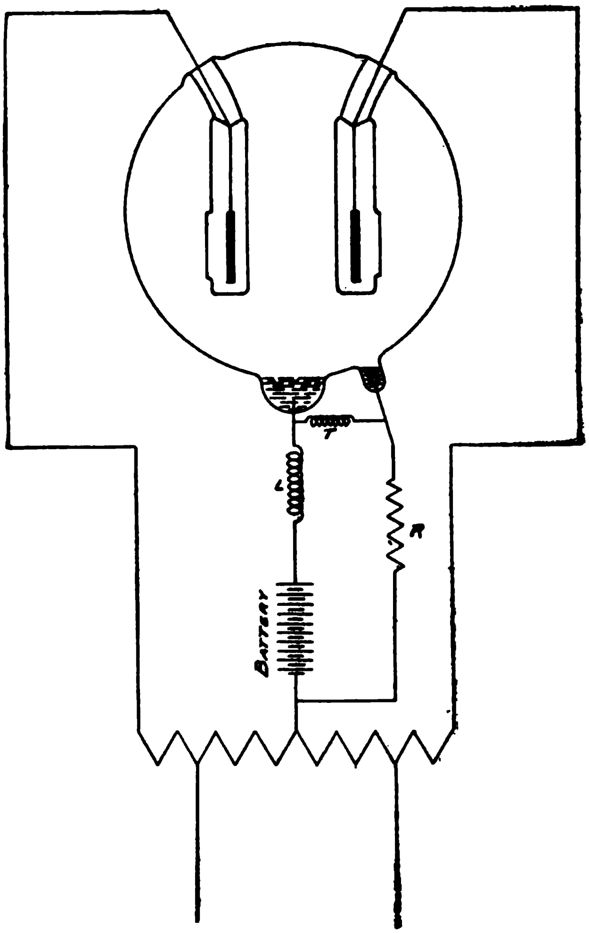


FIG. 5.—Battery starting circuit for converter.

The chief feature of interest of the converter is in the new electrical relation introduced into the receiving and supply circuits by the introduction of the converter. Before discussing this relation, however, it will be well to say a few words on the bulb itself. The heat represented by the 14 volts lost in the vacuum, times the current actually flowing, must be dissipated by the bulb. Artificial cooling means may be used such as fans, immersion in oil, water, etc. Furthermore, a certain portion of this heat is dissipated as radiant energy from the positive electrodes, when these are made of solid material.

Although it is possible to operate converter bulbs, utilizing as seals for introducing current one or more platinum wires of the general character of those used for seals in commercial types of lamps, still it is highly desirable on currents over 20 to 25 amperes to have seals for entering the current to the bulb which shall be able to carry momentarily a great deal more current without cracking the glass. Such a seal has been devised by forming platinum into a cup-shaped piece, having a threaded boss on both the inside and the outside of the bottom of the cup. The glass is sealed to the outer edge of the cup, and the electrode stem and external lead respectively are connected to the two threaded bosses. In this form of seal the current does not pass through the metal which is directly sealed to the glass, so that the glass-platinum joint is heated only by heat conduction.

Parallel Running: Vapor converters can be run in parallel under proper conditions without difficulty. The general condition determining satisfactory paralleling is that the voltage absorbed in each of the paralleled circuits shall increase at least slightly with increase in current, since this insures a division of current between the two circuits. If two devices be used in parallel of such a nature that with increase in current a less voltage is absorbed, such as most mercury vapor lamps, it is evident that the more current one of these devices takes, the more current it tends to take in proportion to the other device on account of its lowered voltage. The bulb of a vapor converter also is usually a device of this character; that is, an increase in current, the temperature remaining constant, causes a decrease in voltage throughout the operating range. In such cases they cannot be connected in parallel directly, since one bulb or the other would instantly take all the current. By the insertion somewhere in the paralleled circuits of a sufficient amount of ohmic or inductive resistance, so that the additional voltage absorbed in the resistance on any increase in current shall be greater than the decrease in voltage in the bulb, satisfactory parallel operation is obtained. Since the voltage change on the bulb would not ordinarily be more than a volt or two, a very slight amount of resistance is sufficient to insure good operation. Obviously, inductance may be substituted for resistance in such parts of the paralleled circuits as carry alternating or intermittent currents.

Since small currents usually require the stored energy of a sustaining coil to maintain them in operation in a converter as well as in a lamp, if a single sustaining coil be placed in the portion of the circuit common to two bulbs connected in parallel, the impulse of the coil, which would otherwise maintain either negative electrode in operation at the time of the momentary tendency to drop out, will be discharged through the other bulb as the easier path, and the first converter will drop out. Consequently, for such types of apparatus it is desirable that each bulb have its own sustaining coil included in the part of the circuit belonging to this bulb alone.

The sustaining coil has the function of supplying energy at low voltage during the zero points of the electromotive force. If one sustaining coil be utilized for two or more bulbs under conditions in which energy is not required for resisting the instantaneous impulses of the negative electrode, it must provide energy for both bulbs. Fortunately, if the coil is powerful enough the energy will be delivered to both bulbs, provided the two circuits are so arranged with resistances or otherwise as to operate in parallel on the generator.

Since a somewhat increased voltage is required in the bulb in starting, to overcome the vapor starting voltage, it is ordinarily more difficult to start one of a number of bulbs connected in parallel after another has been started. For the voltage which is normally lost during running in resistance in other parts of the circuits, is available in a bulb operating singly as an excess starting voltage, while with one of a number of paralleled bulbs operating, since the voltage between the alternating-current and direct-current sides of the other bulbs has been brought to the operating value by the first bulb started, this excess voltage is not available for starting the second bulb.

A number of bulbs designed to operate in parallel can be arranged automatically to cut themselves in and out, either according to the load, or by the accidental dropping out of one of the several bulbs in operation. For this purpose the automatic tilting and starting arrangements used with single bulbs can be controlled by series magnets in the load circuit or in the individual bulb circuits.

Series Operation: A very interesting application of vapor converters is the operation of series direct-current arc lamps from a constant-current alternating supply. Where a moderate number of lamps is to be operated in series, a single bulb will furnish a sufficiently high direct-current voltage; where many arc lamps are to be operated, two or more converter bulbs may be used as shown in Fig. 7, by which arrangement the direct-current voltage of the various bulbs is available in series in the arc circuit. By the use of sufficiently powerful sustaining coils it is possible to utilize current obtained from 25 cycles without material flickering of the arcs. This is an extremely important gain for the users of 25-cycle systems. Bulbs in series may be started as individuals and afterwards thrown in series either on short-circuit or lamp load; or they may be started on a common short circuit or even on the arc

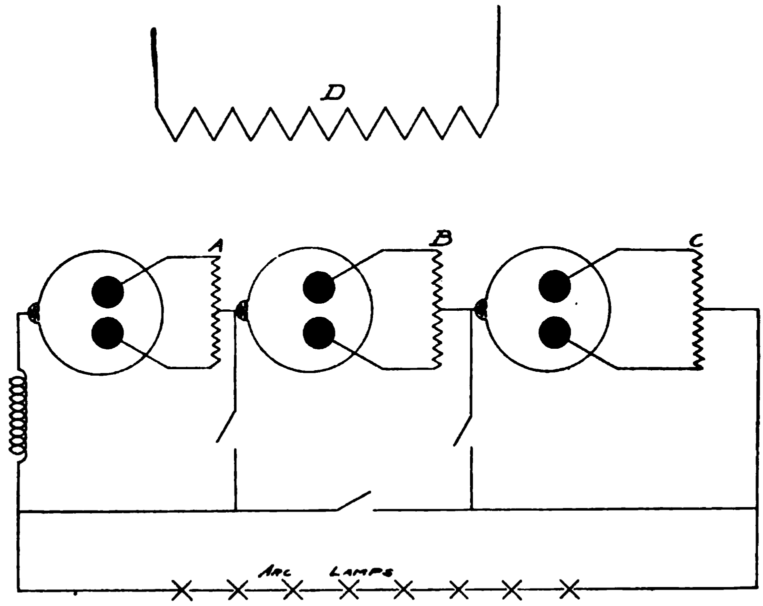


FIG. 7.—Series connection for converter bulbs.
A, B, and C are independent secondaries to the common primary D.
D is fed by a constant alternating current.

circuit itself, the connections for accomplishing this purpose being comparatively easily devised.

Ratio: The "ratio" of a vapor converter is a rather uncertain term, but may be determined in any given cases as follows:

Any single-phase vapor converter operated from a three-wire source, or a transformer with a middle point, is practically equivalent, as far as the direct-current circuit is concerned, to the application of the original alternating-current to the direct-current circuit (including the sustaining coil) with the negative supply alternations reversed. This gives a pulsating voltage, the pulsations being of sine form and running to zero for one instant twice every cycle. The choke-coil smooths out the current pulsations more or less according to its power and the character of the direct-current load. The smoothing action is much greater with a load of ohmic resistance than with a storage-battery or motor or other consumption device having a constant potential feature. The direct-current voltage is measured ordinarily by a direct-current voltmeter which gives the average reading, not the effective reading, of the pulsating voltage, while the alternating-current voltage is measured by an alternating current voltmeter which measures effective values; so that the direct-current instrument will show a reading on the same voltage of approximately $\frac{9}{10}$ that of the alternating-current instrument. This difference appears in the ratio of the vapor converter. Since only one-half of the voltage across the positives is operative at any one time, we have in addition the factor $\frac{1}{2}$ between the voltage across the positives and that in the direct current supply, so that the voltage on the direct-current side, measured by direct current voltmeter, will be 0.45 of the voltage across the positives in the condition assumed. In this case the voltage on the bulb and all auxiliary losses must be included in the direct-current load. If an alternating-current instrument be used for measuring the direct-current voltage a somewhat higher ratio (0.50 as a maximum) may be obtained, according to the degree of smoothing accomplished in the choke-coil. The smoother the direct current the lower the ratio. Both alternating-current and direct-current instruments will, of course, read the same on a perfectly steady current, such as would result from an infinitely powerful sustaining coil. A wattmeter on a vapor converter, having a resistance load, will show a power-factor less than unity, under most conditions, and yet there is no lag between the zero point of the current and the zero electromotive force of the supply. This condition results from a distortion of the current wave resulting from the action of the sustaining coil in the direct-current circuit. The power-factor appears less than unity, since the distortion of the current is equivalent to the addition of higher harmonics which being of a different periodicity from the supply can deliver no real energy while still increasing the effective value of the current. These matters are of great interest and practical importance, but would require too much space for further discussion in this paper.

The ratio of the current in the direct-current load to that in the supply circuit is one-half, except for the variations of instrument indications which result from wave-form distortion, and except for the fact that a certain amount of current is supplied to the load by the sustaining coil at periods of low supply electromotive force which current does not appear in the supply. It is here assumed that the supply is connected directly across the positives.

Current Control: Where a direct current of constant potential is desired through the use of a vapor converter, this can be properly accomplished by the direct connection of the work circuit through the converter and a sustaining coil, and the constancy of the direct current potential will be directly equal to that of the alternating-current supply, since though 15 volts are absorbed by the bulb this value does not increase with increase of current.

In cases where it is desired that the direct-current potential shall be continuous, even when no direct current is drawn, it is evident that with single-phase converters auxiliary means must be supplied to keep the bulb in operation. This is accomplished in a number of ways, for instance by a shunt which is kept always running, or by providing a separate circuit with a separate source of electromotive force passing current through the bulb from separate positive electrodes and utilizing the same negative as the main circuit.

Where regulation of the current is desired, as in operating storage-batteries, it is not sufficient to provide a constant potential alternating-current supply, but some means equivalent to the adjustable resistance ordinarily used in direct-current systems for this purpose is necessary. This can be easily accomplished by the introduction of inductance, preferably adjustable in the main positives or in the supply. Since the voltage taken up by the resistance or inductance is fixed as the difference between the supply voltage and the direct-current potential by changing the ohmic value of this "resistance" or backing, we, of course, alter the current strength.

Physical Explanations of Short Circuits in Converters: The general assumption or hypothesis upon which the reactions of the vapor apparatus are explained in the early part of this paper needs some amplification in connection with the converter. There is a tendency for the negative electrode resistance to fail in one of the positive electrodes in some types of bulbs during the time that it is impressed with a negative voltage thus causing a short-circuiting of the supply. One way to eliminate this difficulty is to interpose around the electrode a screen to obstruct a direct line from the non-operative positive electrode to the negative electrode or to the bath of the current between the negative and the other positive electrodes. Furthermore, this tendency is very much reduced by the elimination of the last traces of foreign gases or vapors originally in the bulb. This action can be easily explained if we assume, as already described in connection with the arc in air, that positive ions accumulating on the surface of a positive electrode under electric strain will cause the negative electrode starting resistance to fail.

Thus we may assume that a part or the whole of the residual gas (as distinguishable from mercury vapor) remaining within the bulb becomes ionized by the operation of the converter. Then the electrons will be attracted to the operating positive electrode, while the positive ions will be attracted to the other positive electrode since that is at a lower potential than the negative, where they may be capable of initiating a short-circuit. The introduction of the screen above mentioned will evidently prevent the positive ions from reaching the negatively charged positive electrode since they are attracted thereto in straight lines and will be held by the force of attraction against the surface of the screen. If there be an excessive quantity of ions, however, some of them may find their way around the shield, especially in view of repulsion by those initially accumulated on the screen, and finally cause a short-circuit.

The writer wishes to make an apology for the very incomplete and rather heterogeneous nature of the information given in this paper, but the very great amount of space and effort that would be required for giving a complete discussion of this apparatus is prohibitive, and it is hoped that such as is given will be of value.

Much information which has been published elsewhere has been used here for the sake of having such data consistently stated and collected in one place.

DISCUSSION ON "SOME FUNDAMENTAL CHARACTERISTICS OF MERCURY VAPOR APPARATUS," AT MILWAUKEE, WIS., MAY 31, 1906.

C. P. Steinmetz: As stated in the concluding sentence, this paper is not confined to new matter, it is also somewhat historical in that it reviews in part much of the work that has been done with mercury arc apparatus. As regards the statement of facts contained in the paper, in general I agree with the author; but with his interpretations and explanations of facts I must disagree to a considerable extent, partly for the reason that the paper describes as features of a special class of phenomena features which are characteristic of a far more general class of phenomena; that is, characteristics of arcs in general, the common carbon arc, well known to us for a century, as well as the mercury arc. Furthermore, well-known features are re-explained in connection with the mercury arc by the introduction of new terms; for instance, the so-called cathode or negative resistance, which is nothing more than a reiteration of the fact that an electric arc does not start itself, but must be started. That was known a century ago by Davy, when he drew the first powerful arc by putting battery terminals together and then separating them. But Davy did not introduce the term "negative resistance," he merely stated the phenomenon, which since that time has been used by every designer and operator of arc lamps, though I do not think many of the designers and operators have ever heard anything about negative resistance.

Some of the explanations in the paper encroach on the field of metaphysics. From an engineering point of view I do not see any advantage in entering this field, which for centuries has been the playground of human thought. My experience protests against it, and as far as possible I like to explain phenomena in what I consider as a more common-sense way, as conclusions from the law of the conservation of energy, conservation of matter, etc.

Taking up the paper a little more in detail, the first three pages contain as description of the electrical characteristics of the mercury-vapor arc in a vacuum, what are really the electrical characteristics of any arc, the carbon arc, the magnetite arc, or any other arc, in air or otherwise; that is, a drop of potential at the two terminals, which is approximately constant and independent of the current, and a drop of potential in the arc proper, the arc flame or vapor stream, whatever you may call it, which is of the character of a resistance, but the resistance of a conductor which makes its own path. Two years ago, before the International Electrical Congress at St. Louis, in a paper on the electric arc, I discussed these phenomena, and gave the theoretical considerations leading to the derivation of the equation of the volt-ampere characteristic of the arc, of which a special case is the carbon arc; another the magnetite arc, known to all of us, and another special case again in the mercury vapor arc as shown on the third page of the present paper.

The matter is very simple if you do not introduce any mysterious conceptions, but look at it merely from the point of view of the law of conservation of energy. The power available in the arc-stream is the volts times amperes. This power has to be radiated from the arc-stream, and the power radiated from the arc stream is proportional to the surface of the arc-flame, and depends on the temperature of the arc-flame. This immediately gives an equation relating the surface of the arc-stream and its temperature, with the volts and amperes. Furthermore, the section of the arc-stream, or, more properly, the volume of the arc-stream, is proportional to the current, and this gives the second equation required. From these two equations you can derive the equation between volts and amperes in the arc, for any condition of operation. For instance, in the case of constant pressure; that is, constant temperature of the arc-stream, the temperature of the boiling point of the negative material, you get the characteristic curve of the carbon arc or magnetite arc. Or you can derive the equation between volts and amperes for an arc of constant cross-section; that is, the arc vapor pressure varying with the current, and the temperature varying with the current. This leads you to an equation giving the curve on the third page of the paper; with reasonably fair approximation this can be represented by the following equation:

$$e = e_0 + \frac{l}{a\,d - b\,i - c\,\frac{d^2}{i}}$$

where:

e = e.m.f. consumed by mercury arc,
i = current,
e_0 = 13 volts = potential drop at terminals,
l = arc length, in inches,
d = arc diameter, in inches,
and: a, b, and c are constants:
a = 1.68.
b can have two different values, one:
b = 0.114, for a mercury anode, the other,
b = 0.066, for a graphite, iron or other solid anode,
c = 1,3.

The constant b also depends on the size of the condensing chamber, and the constant c, to a limited extent, on the temperature of the air surrounding the arc. This equation and the discussion of the deviation of the actual curve at very low and very high values, from this rational equation, is given in my paper read before Section D of the International Electrical Congress. The paper can be found in the proceedings of that Congress.

I may say that this curve is a characteristic volt-ampere curve of the mercury arc in permanent condition; that is, the relation between volts and amperes, after a sufficient length of time has elapsed to reach permanent or constant condition. From this curve it would seem to follow that at 4 amperes or more the mercury arc could be operated at constant impressed voltage, without steadying resistance, because the voltage rises with the current. This is not the case. The mercury arc, like any other arc, is unstable at constant impressed voltage. The reason is that the rate of change of electromotive force over change of current, is negative throughout. In other words, if you change the current from 4 to 4.5 amperes, the voltage drops, and then gradually rises again to the voltage given in this curve for 4.5 amperes: The $\frac{d e}{d i}$ is negative, as in any arc. The value of $\frac{d e}{d i}$ increases with decreasing current; that is, the volt-ampere characteristic becomes very steep with low currents. From this follows, at low current, at limited impressed voltage, an instability of the arc. This instability is an inherent feature of every arc, from the carbon arc at 3500° cent. down to the mercury-vapor arc, at something between 200 and 250° cent. It is more pronounced in the magnetite arc at about 2000° cent. than in the carbon arc, and more pronounced still in the mercury arc, due to its still lower temperature. But any arc, if you run down to low currents at limited supply voltage, has the disagreeable feature of suddenly putting itself out; but it may jump and start itself again if the voltage is high enough. A remedy for this is the introduction of inductance in series with the arc.

This matter was fully investigated by Professor Elihu Thomson in the early days of arc lighting. He took out a patent for the use of inductance in series with direct-current arcs to steady the arc and keep it from rupturing itself. I believe the patent expired some years ago.

The feature of a rotating spot on the negative terminal, described on the fourth page, is not a characteristic of the mercury arc; every arc having a liquid of fusible negative electrode shows it. In the development of the magnetite arc lamp, one of the most difficult problems which had to be solved was to eliminate the flicker due to the rotating spot on the negative terminal. It has been successfully done, but it shows that this feature is not characteristic of the mercury arc alone, but is inherent to all arcs having a fusible negative. It is the result of mechanical causes, the law of action and reaction; in other words, it is the effect of the recoil or reaction of the arc-blast, as I have described in the paper already referred to.

The " negative resistance " or " cathode resistance," is a new and I believe unnecessary way of saying that the arc does not start itself, that it has to be started; this is a very well known phenomenon, and is nothing but a necessary conclusion from the law of conservation of energy. An electric arc is the passage of current between two terminals, through a conducting vapor bridge consisting of the material of the negative terminal, issuing from the negative. The electric spark is the passage of current between terminals through the medium of the gas or vapor filling the space. The spark will pass as soon as there is a sufficient voltage, because the conducting medium is there. The arc cannot pass without first establishing the bridge of conducting vapor from the negative to the positive. This requires the expenditure of energy, the latent heat of evaporation, kinetic energy of motion of the vapor stream, etc., and this energy must be expended before the arc can exist. Before the current flows, no energy can be expended by the electric circuit, and therefore it follows that the electric arc by the law of conservation of energy cannot spontaneously start, but must be started.

There are many methods of starting an arc. A few are described in the paper. One is to bring the conductors in metallic contact with each other and so establish a circuit, and then separate them, the current flowing and the energy required to produce the vapor bridge being derived from the electrical energy of the current. Another well known method, described on the seventh page, is to raise the potential across the terminals so high that the energy of the electrostatic field between the terminals, or the dielectric displacement current, represents sufficient energy to produce the vapor bridge—to jump a spark across the terminals, which will be followed by the arc if there is sufficient power behind it. This is a way to start arcs, which occasionally happens without the wish of the engineer, and at undesired places, as between the conductors of a transmission line. Hence the general characteristic is that the energy of the vapor stream must be supplied. It can be supplied by another arc. An auxiliary arc may be produced, as it was done in some older types of mercury-arc lamps, the auxiliary arc supplying the vapor stream which is used in the main arc. The operation of the mercury-arc rectifier depends on the fact that there are two arcs continuously alternating; one of the alternating-current half-waves passes from the common negative to the one anode as positive, and the next half wave passes to the other. The vapor stream of the latter wave is supplied from that of the former, and so on, so that each half-wave arc starts the next, by supply-it with the vapor stream. Another way to start an arc is this: take a vacuum tube with mercury terminals, with the voltage on, and shake the tube rapidly; the rapid shaking in a high vacuum (it must not be a perfect vacuum, but nearly perfect) produces static sparks due to the mercury hammer, and these sparks produce sufficient conducting mercury vapor to start the current, especially if the electrostatic capacity of the system is increased by coating the outside of the tube at the mercury terminal with tin-foil, and connecting this with the opposite pole. So the mercury arc can sometimes be started by mere shaking, if the vacuum is just right. Another way is to bridge the space between the negative and positive terminals, by a conducting carbon filament and raise it to a sufficiently high temperature; for instance, an inverted *U*-tube with two mercury terminals and a U-shaped carbon filament dipping into both, will start, if connected across a voltage raising the filament to full candle-power. This temperature is sufficient to produce the conducting mercury vapor to start the arc. Afterward the filament can be cut out by mercury vapor pressure or other means. Some such lamps, based on the starting by an incandescent filament, I designed some six or seven years ago. The plunger type of mercury arc lamp, as used on series circuits, occasionally starts in this manner, if for some reason or other the plunger sticks in starting. The general requirement of starting any arc is to supply the energy of the vapor stream by some source before the arc exists.

In regard to the author's exposition on " The Physical Nature of Vapor Conduction," I have read it twice and have failed to catch its meaning. There is a little more metaphysics in that section than I am used to. In engineering exposition I have always endeavored to explain everything in such a manner as to produce a physical conception of it, and therefore the author's phrase, " forcing out negative electrons from a cathode " is too much for me. So also the statement that:

> According to the assumption it should be noticed that the source of electrons is not the ionization of the gas or vapor within the container, as in many other experiments, etc.

merely means in plain language, that in the arc the current is carried by the vapor of the negative terminal, and not by the gas which fills the space between the terminals, as is the case in the electrostatic spark. Here again I see no reason to circumscribe by hypothetical conceptions as the ionic theory, facts which are far plainer without it. It seems now to be the fashion among engineers to look at everything as done by ions.

In regard to the spectrum of the mercury arc, I wish it were as stated. But the orange-yellow lines have a wave length of about 57 microns; that is, are on the green side of the yellow line of the sodium spectrum, and the yellow line is greenish-yellow. I would say rather that the lines are greenish-yellow, bright green, faint dark-green, blue, and two violet lines. Several of the lines are doublets or possibly triplets.

In regard to the disclaimer in relation to the measuring of candle-power of mercury-arc lamps, I consider that as unfortunate, because it is the usual custom. Whoever invents a "new and revolutionary " method of lighting, of wonderful efficiency far higher than anything ever dreamed of, always says: the photometer does not show the efficiency of the wonderful light; you have to look at it to believe it. The fact is that the mercury lamp does not need that disclaimer. It is indeed of an extremely high efficiency. You can measure it by getting far enough away so that the inverse-square law can be used. If you use it for only short distances, that does not hinder you from measuring the total flux of light issuing from the tube at a sufficient distance to apply the inverse-square law. We have obtained good results with the ordinary paraffin block photometer, a sheet of tin-foil cast into a block of paraffin and held between the two sources of light. It is moved until both sides are illuminated with equal brilliancy; the one from the incandescent lamp appears yellow and the other green. I have tried it, and had friends try it, and it is remarkable how close you can compare the yellow incandescent lamp with the green mercury arc lamp with the paraffin photometer, by continuously moving it slightly until you get a position of equal intensities. Another method of comparing values is the luminometer which, while not so accurate as the photometer, is accurate within a few per cent. The luminometer can be used to compare mercury-arc lamps with other lamps. Luminometer tests gave the relative efficiency of the mercury-arc lamp, using 160 watts to the lamp, 125 watts to the arc, and running from a 4-ampere constant-current series circuit, as slightly higher than the 450-watt enclosed direct-current carbon arc. That gives a measure of efficiency, which certainly shows the mercury lamp as very satisfactory.

The mercury-arc rectifier, or vapor converter, as it is here called, of the constant-potential type, I do not need to discuss, as it is a commercial article, used extensively for charging automobile batteries and supplying direct-current power to telephone exchanges. On the constant-current mercury-arc rectifier, I had the pleasure of reading a paper a year ago at the Asheville convention, and discussed it there. Regarding Fig. 7, three converters in series, it is an arrangement of getting a higher voltage on the system than can be obtained from a single converter; since, however, as shown in my paper, 10,000 volts direct current can be produced by a single rectifier tube, and numerous constant-current rectifier circuits are in operation at from 4000 to 7000 volts, and that is probably as high a direct-current voltage as any one would expect to use, I believe practically all of the arc lighting work can be handled with a single tube. As regards the short-circuiting of the rectifier, my experience is that the tendency to short circuit at high voltage can be entirely eliminated by the design of the rectifier, and need not be feared. There is practically no voltage limit to the power which can be rectified; I think with moderate power we can get as high as 25,000 volts direct current through the mercury-arc rectifier without short circuiting.

President Wheeler: Will Mr. Wirt tell us something about the commercial experiences of the lamp?

H. C. Wirt: Eight or ten circuits at different places have been in operation from three to five months. At first there was considerable trouble with the breaking of the rectifier tubes, due partly to static effects. At present each system is in the hands of an expert, with one or two exceptions, and I believe the system is going to be generally satisfactory. The standard magnetite direct-current lamp is used on the system.

P. H. Thomas: Dr. Steinmetz seems to wish us to infer that all our mercury vapor apparatus is an old story, and there is no novelty in it. I do not know why it happened, then, that we all, including Dr. Steinmetz, had to wait until Mr. Hewitt showed us how to use it. Seriously, there is undoubtedly a similarity between the carbon arc or any other arc, and the Cooper Hewitt mercury vapor apparatus, but there are also differences, differences so great that a person who might understand the atmospheric arc thoroughly would have practically little or no help from such knowledge to enable him to utilize the mercury vapor apparatus. Substantially, they are not the same art. They have very different characteristics. The necessity of a high voltage, or touching and separating electrodes in starting, is characteristic both of the arc in the air and the mercury vapor lamp, but the causes are not the same. The resistance in starting the mercury vapor usually resides wholly at the surface of the negative electrode and not in the path between the electrodes. In the atmosphere arc, on the other hand, the starting resistance of the arc is largely the resistance of the air between the electrodes. If you bring the gap down so that the electrodes almost touch, the arc will start at very low voltage. That shows that you do not have the resistance residing at the negative electrode itself, as in the mercury apparatus.

I agree with most of what Dr. Steinmetz has said. As he has said, much of the matter that has been presented here has been given before—the greater part of it first by Mr. Hewitt.

It is a matter of metaphysics, if you wish to put it that way, whether we consider a conducting current to be due to a conducting vapor bridge, or whether we consider electrons to be taken from the negative electrode and passed through to the positive electrode, but I think we of the AMERICAN INSTITUTE are glad sometimes to be metaphysicists. By these theories I think we are getting at what we want, however, and if there is no way in which we can do it except through metaphysics, there is no objection.

In regard to the measurement of the candle-power of the Cooper Hewitt lamp, or lamps of this character, I would say that it is true that lamps can be measured at such a distance as to have the law of inverse square hold, and it is true that there is no material difficulty in getting an exact setting, with the mercury vapor lamp on one side of a screen and an incandescent lamp on the other. But since the object of measuring candle-power between different lamps is to give an idea of the relative effectiveness of the light which he will get from it (I am considering commercial tests) it would seem wisest to use such a method of measuring the power of a light as will most nearly indicate its effectiveness, which would not be such a long-distance method.

As I have not come across any vapor converter installations supplying 7000 volts, direct-current arc circuits, I would ask Dr. Steinmetz where they are located?

C. P. Steinmetz: Portland, Ore., and Glens Falls, N. Y.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee Wis., May 28-31, 1906.

AUTOMATIC SAFETY DEVICES FOR STEAM-ENGINES, TURBINES, AND MOTORS.

BY CHARLES M. HEMINWAY.

The increasing use of automatic appliances is a noteworthy feature of the tendency in engineering development. In the electrical industries automatic appliances are largely used, and the results have been so good that we find the peculiar flexibility of electrical systems leading to their use for automatic apparatus in other lines of work.

There is probably not an electrical system to-day, either for transportation or power purposes, for lighting, telephone, or any of the other various applications of electricity, in which some automatic devices are not used. These appliances may take the form of regulators or governors for controlling the performance of a machine. In railway work they are extensively used for signaling.

Though the application of automatic appliances is varied and extensive, it is the purpose of this paper to touch upon one branch only; that is, to prevent damage that might be caused by unusual or unexpected conditions. In the equipment and operation of power plants the two factors that are first given consideration are efficiency and economy. The factor of safety also receives attention and is becoming more generally recognized as a necessity, for without it the two former are of little avail, yet in the particular branch to which I wish to direct your attention it has not been so generally introduced as in some others.

Automatic stops bear the same relation to steam-engines and turbines that safety-valves do to boilers, or circuit-breakers to dynamos. It is probable that the universal adoption of circuit-breakers closely followed an unusually large number of accidents; similarly, the alarming increase in the number of runaway engines and resultant fly-wheel wrecks will doubtless hasten the general use of safety devices for engines and turbines. There is a general impression among engine owners that the governor on the engine is a safety device, and is capable of providing for all emergencies; this is a fallacy, as statistics show that about 200 reciprocating engines and several turbines and synchronous converters have run away in the past 20 months—and all had governors.

The governor is designed to keep the speed of an engine constant under variations of load, but as most governors are arranged to operate by centrifugal force they cannot act instantly, as when the load goes off suddenly; it is for this reason that there is real need for a safety device entirely apart from the governor that will act quickly in case of emergency.

FIG. 1.—Monarch engine-stop; the device applicable to the throttle, and operated by gravity.

Some of the causes of recent fly-wheel accidents are: breaking of main belt; loose governor pulley; reversal of dynamo; sticking governor; but chiefly the breaking or slipping of a governor belt and the sudden relief of the load.

Some plants now carry fly-wheel insurance, which includes periodical inspections. This furnishes monetary protection, but does not insure safety; for in spite of the inspections fly-wheel accidents continue to occur. It will be readily seen that while inspections may detect a weakness in some part of the engine equipment, or the inefficiency of an engineer, many things may happen between the inspections. While the insurance pays the property damages and personal injuries, it does not make good the losses from non-production pending repairs to the plant, nor the wage-loss of the employes. Obviously, then, the remedy lies in the providing of such means as will prevent accidents.

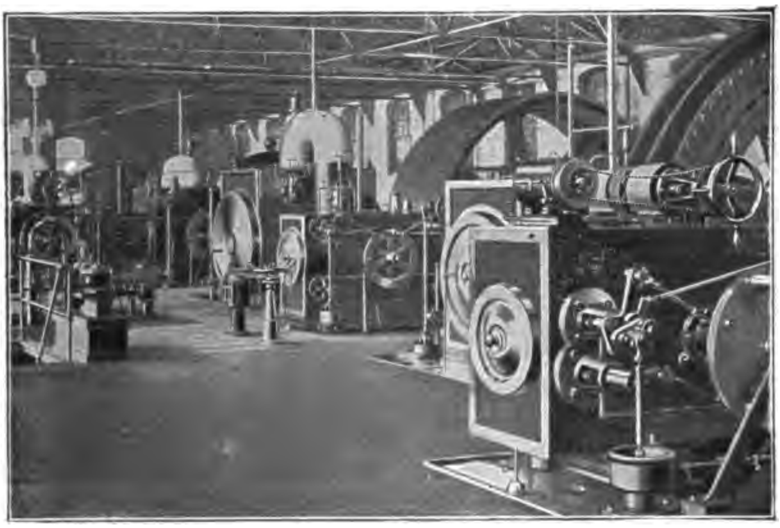


Fig. 2.—Application of Monarch engine-stop to horizontal and vertical valve stems.

There is still another use for the same device; namely, to shut down the engine from a distant part of the plant by pressing a switch. When an employe is caught in the machinery, when the belting breaks, when the shafting or the machinery is out of order, when a cylinder-head blows out—in all cases when it would be impossible to reach the throttle promptly, the automatic stop is invaluable.

Engine-stops are of varied design and are applied in many different ways. Most of them are designed merely to stop the engine mechanically in case of over-speed. There is a growing tendency toward the use of electric current to trip the engine-stops, thus allowing them to be operated from any number of points.

One stop is designed to be attached to the governor column, and, upon being tripped electrically, opens a steam-valve, allowing steam to enter a small cylinder against a piston, which raises the governor balls to their maximum position, thereby cutting off the supply of steam to the cylinder. This is a reliable stop and in connection with a speed-limit device is very effective.

The speed limit consists of a centrifugal device connected to the engine-shaft by a chain-drive; it is in circuit with the engine-stop and can be set at any predetermined speed; when this speed is reached, electric contact is made tripping the engine-stop.

Other forms are applied to special valves which must be placed in the steam line and operated as an auxiliary to the main throttle-valve. The valve in these forms is usually closed by steam pressure, the steam being admitted to some small cylinder and moving a piston in closing. These forms have many points in their favor but care must be taken to keep them in order, and the expense of inserting a special valve in a steam line already erected is rather great.

Another type of engine-stop operates directly upon the throttle-valve, and can be easily applied to any engine without interfering with its regular work. This stop is bolted to the engine-frame at any convenient place, and is attached to the valve-stem by means of a sprocket-wheel and chain. As the valve is opened, a cable, to one end of which is attached a weight, is wound on a drum on the stop and is held by a pawl which engages in a ratchet-wheel. When the stop is tripped electrically the weight is released, revolving the sprocket wheel and thus closing the valve, a dash-pot in the stop forming a cushion to prevent jamming the valve. This, in connection with the speed limit, forms a very satisfactory device; and as gravity is depended upon for doing the work there is nothing that is likely to fail in operating.

Another engine-stop also operating on the throttle and connected to it with a sprocket-wheel and chain, similar to the one just described, is operated by an electric motor, ¼ h.p. or ½ h.p. This is more expensive on account of the motor and the necessary generating apparatus. The current can be taken from bus-bars, but in order to insure reliability it is advisable to have the engine furnish its own current. This kind of stop is particularly desirable on units having 12-in. valves, or larger.

In order to insure protection for all contingencies, an automatic vacuum-breaker is wired in the circuit with any of the engine-stops where condensing engines are equipped with this safety device, so that if the engine should be shut down automatically the automatic vacuum-breaker will operate simultaneously with the engine-stop, opening the exhaust to the atmosphere.

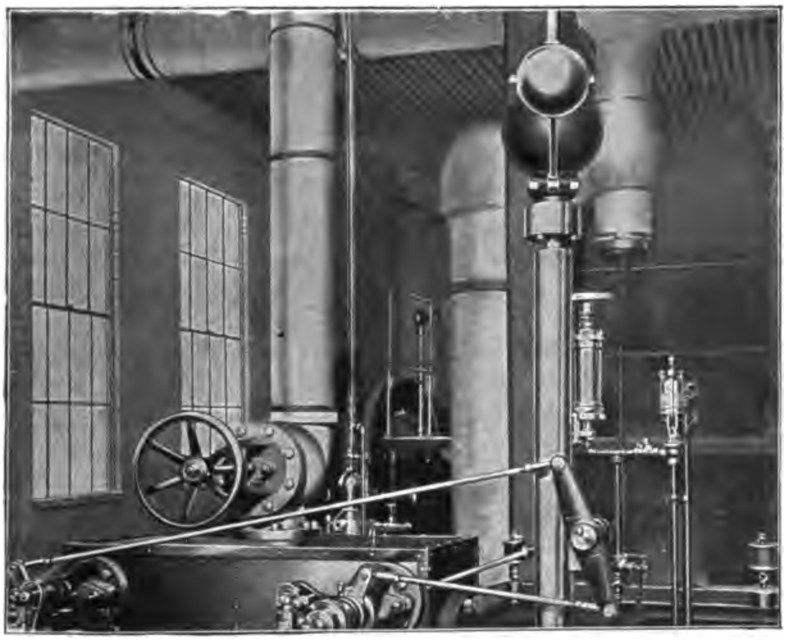


FIG. 3.—Corliss engine-stop, applied to governor column of Corliss engine. This stop is operated by steam.

Another provision for safety has been provided in an automatic circuit-breaker trip which also is wired in the circuit with the engine-stop. In plants where engines operate generators in multiple, the closing of the circuit, either automatically by the speed limit or from any of the push-switches in the system, operates not only the engine-stop, but also the circuit-breaker trip, cutting out the generator to prevent it from running as a motor.

Where electricity is used in tripping a stop it is desirable to have some means of testing the circuits and strength of the batteries. A very satisfactory system is in use for this purpose; a small slate testboard having upon it a switch for tripping the stop, a buzzer or a lamp, and two small key-switches for testing the circuits. The buzzer is of high resistance, and if the batteries are getting weak an intermittent response of the buzzer will indicate this, and yet current for at least 24 hours is still available to use the stop, allowing sufficient time for recharging the batteries.

A failure of the buzzer to respond to the pressure of the test-switch indicates a break in the wiring, but pending repairs to the wires it is possible to shut down the engine either automatically by the speed limit or from any of the push-switches. This is accomplished by throwing the wires from multiple into series for a test, so that though the indication of a break in the circuit is instantly detected, the engine-stop system is still in commission. This is one of the strongest points in favor of engine-stops, as it insures reliability; the safety device cannot be crippled by weak batteries or broken wires, but is always ready for emergencies.

There is also another testboard in use, substantially the same as the one just described, but with the addition of a solenoid switch. This is designed to use high-tension current to operate the engine-stop with battery in reserve. It can be used on any voltage from 110 to 550. The voltage is cut down by means of resistance coils on the testboard, and the current going through the solenoid holds the armature against the magnets operating on the generator.

If the generator furnishing this source of current is shut down or a fuse blows, the armature falls by gravity to the battery terminal and the engine-stop system is then operated from the battery circuit until the direct circuit is again in service. This system adds an additional safeguard from the fact that there are two sources from which to operate the engine stop. It is particularly desirable in factories, where the generator current is not on during the day. It lengthens the life of the batteries, as they will be used only a portion of the time.

While this paper is confined more particularly to the application of automatic safety devices to engines, the same appliance in modified forms is working successfully on steam turbines, synchronous converters, motors, gas- and oil-engines, and water-wheels.

It has frequently been said that automatic safety stops are an expense that do not add to the efficiency or economy in the operation of the plant. A few facts bearing on this point will serve to prove the contrary. First, certain types of stops are recognized by the liability insurance companies, and a reduced rate on employers' liability insurance is allowed; secondly, where automatic safety stops are used, fly-wheel insurance can be dispensed with. Here are economies that begin to accrue the moment the stop is installed.

Admitting that no plant is entirely safe from accident; when the emergency does occur the small amount invested in stops will save from ten to twenty times their cost in damages prevented. Records show that large property losses have been averted and many lives saved by their prompt and efficient operation.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Milwaukee, Wis., May 28-31, 1906.

NOTES ON THE LIGHTING OF CHURCHES.

BY EDWIN R. WEEKS.

Few inventions have been more far reaching, or more generally adopted, than those pertaining to artificial illumination. Places of amusement, public buildings, parks and boulevards, expositions, steamship lines, railroads, and residences—all vie with each other in the extent and decorative features of their lighting. Science has long since formulated the principles upon which improved methods are based, and inventors and factories have supplied the apparatus; yet in one class of buildings there has been little, if any, effort to make full use of the possibilities of artistic and effective illumination. Churches are still characterized by the notoriously poor lighting inherited from the dark ages when the printed word was unknown.

Next to the acoustics, there is no feature of church architecture of greater importance than that of lighting. While defective acoustics are an annoyance at all services and deprive parishioners of much of the benefit and enjoyment for which they attend church, they do not belittle the architecture or deplete the exchequer. An inadequate system of lighting, however, is not only an extravagance, but it practically eliminates the beauty and effectiveness of capital, entablature, and vaulted roof with their costly decorations and symbolism.

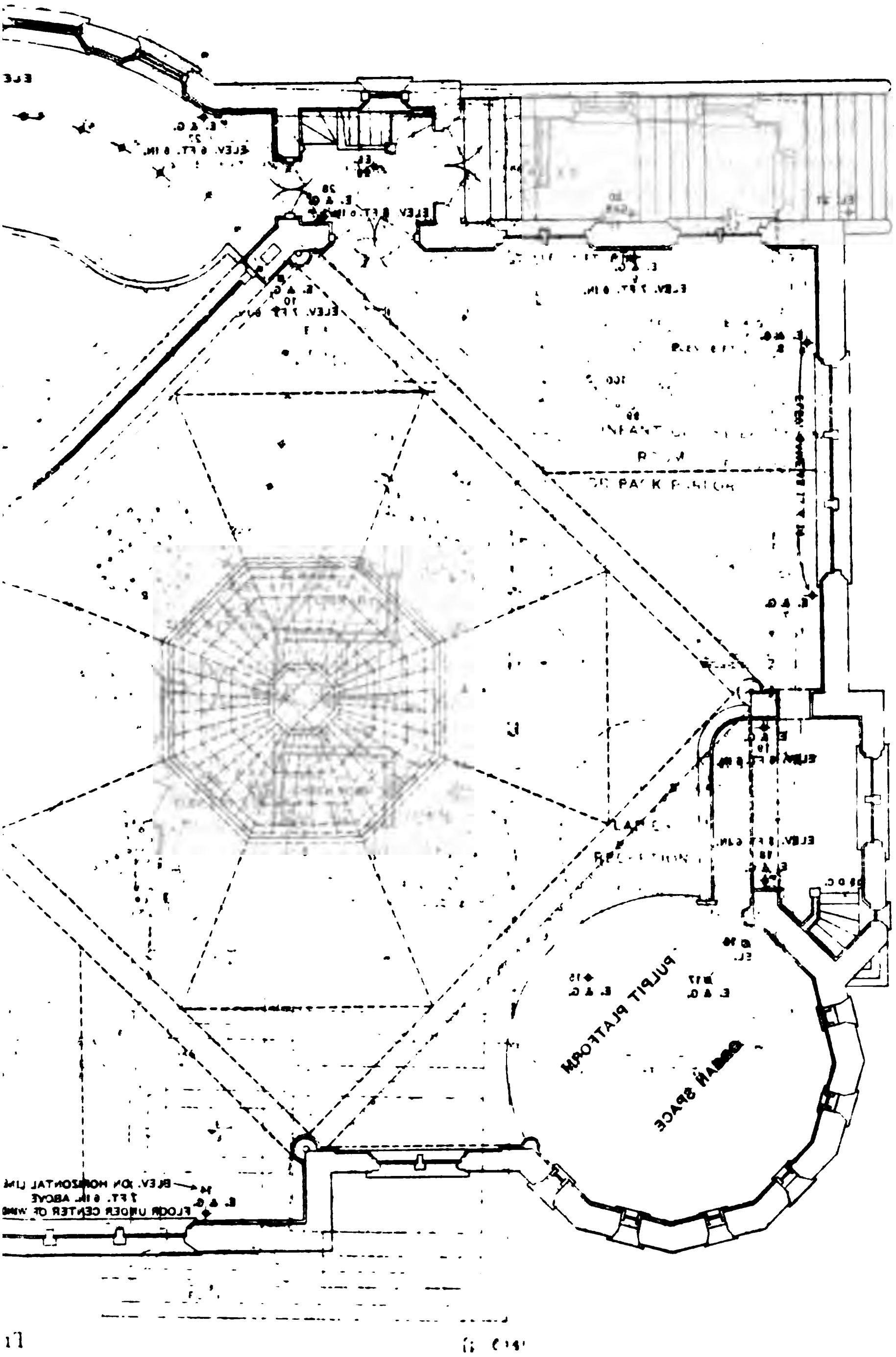
The proverbial " dim religious light " of ecclesiastical structures is due to several causes. Architectural limitations produce an unequal, and at times, insufficient distribution even of daylight, and the immense distances through vaulted dome and transept make uniform artificial lighting by the old methods of suspension practically impossible. Again, the immemorial custom of using sombre woods and gloomy wall-tints adds to the difficulties; and the inertia of precedent and a false economy continue these obsolete practices long after better and more scientific methods are available.

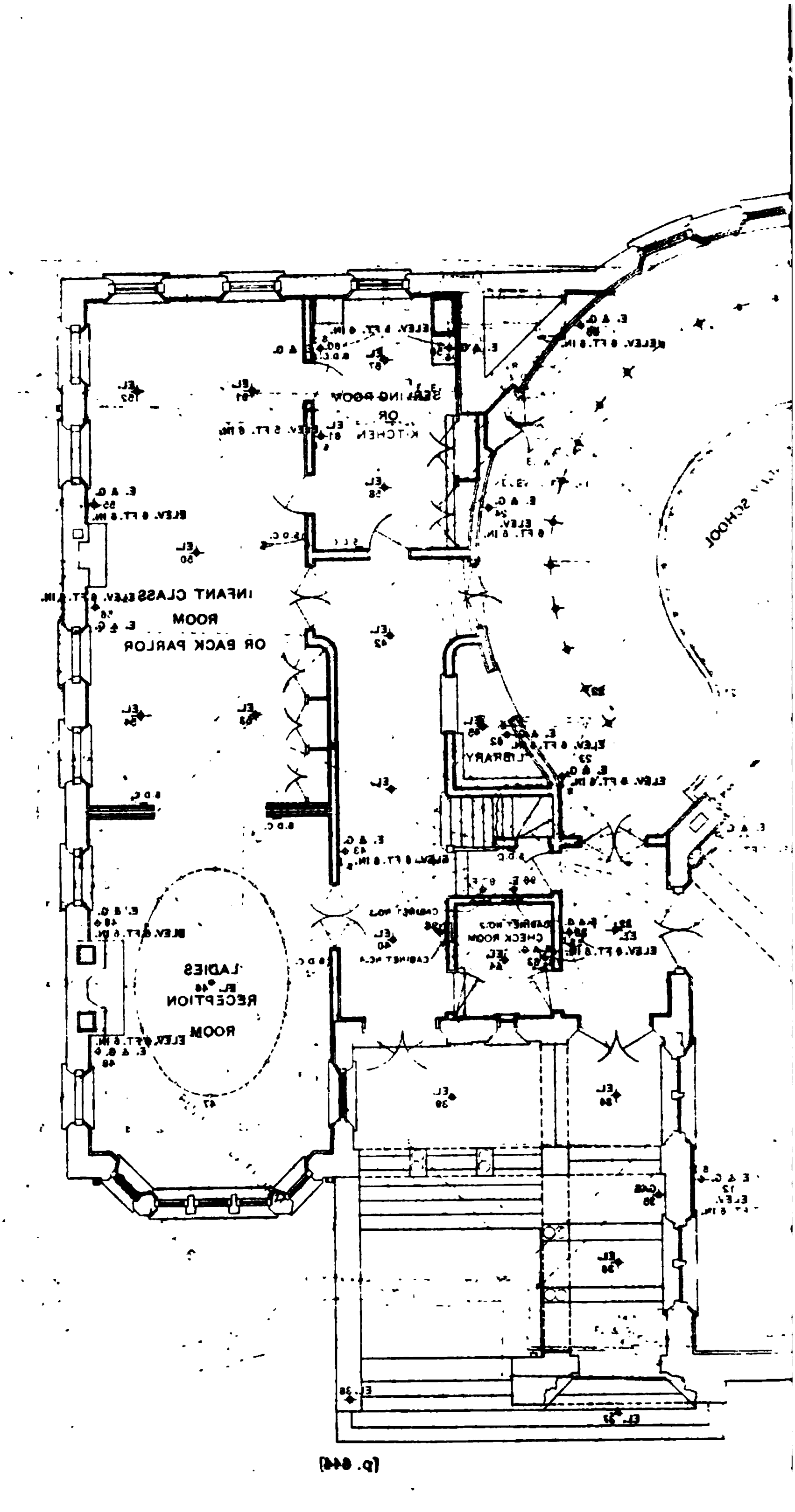
Suspension devices have persisted from the time of the torch and tallow dip, although the advent of a most flexible medium has made their use inexcusable. Chandeliers are, at best, costly in installation, wasteful, and hazardous in operation; grouping the lights at a few points, usually in the plane of vision, they are painfully obtrusive and inartistic. In churches upon which large amounts have been expended to create spacious and inspiring auditoriums, it is not uncommon for the chief impression to be that of glittering pyramids, completely nullifying the sense of restful worship which should characterize such an interior.

It is, of course, true that lamps in receptacles flush with the ceiling or high wall-panels give less light in the reading plane than do the same lamps suspended a few feet above this plane; but when so placed they may be made to serve the purposes of uniform distribution, of didactic symbolism, and of displaying and even forming an important part of the architectural and mural decoration. These advantages furnish ample consideration for the cost of the additional lamps required to give the light needed in the reading plane.

The chief requisites in church lighting are adequacy and uniformity. The maximum variation throughout the auditorium should not exceed 20 per cent. This uniformity is seldom secured with daylight, but there is no reason why it should not be attained with artificial light, since electricity can easily be transmitted to all parts of the building and practically moulded to suit the demands of distribution as well as the needs of the architecture and decoration. In this respect the electric light may be said to " beat daylight."

The amount of light in the reading plane should not be less than two candle-feet; that is, about twice the light required by the average person for reading without the impairment of eyesight. The frugal vestryman may ask, " Why double the amount of light? " The answer is that the best and most attractive lighting is not only an excellent advertisement and a means of grace, but it may be quite economically employed in assembly rooms which are occupied but six or eight hours each month, if the controlling devices be properly designed and used. Furthermore, a religious gathering, more than any


PULPIT PLATFORM
ORGAN SPACE
INFANT ROOM
OR PACK ROOM
LADIES' RECEPTION
ELEV. 7 FT. 6 IN.
ELEV. 6 FT. 6 IN.
E. & G.
ELEV. ON HORIZONTAL LINE 7 FT. 6 IN. ABOVE FLOOR UNDER CENTER OF WIND


SERVING ROOM OR KITCHEN
INFANT CLASS ROOM OR BACK PARLOR
LADIES RECEPTION ROOM
LIBRARY
CHECK ROOM
CABINET NO. 2
SCHOOL

[p. 644]

other concourse of people, contains persons of all ages, many of whom have failing eyesight, and all of whom should have sufficient light to enable them to read the lines of text or hymn. With an expense of two dollars an hour for light which gives perfect satisfaction to every one in the audience, and makes of the auditorium a beautiful and attractive place for young people, there can be no question of extravagance. The extravagance lies rather in employing a system which although it may cost half as much, fails to give satisfaction to any considerable number of the congregation.

A well-planned layout of switch-control effects a great economy in any installation; this is especially true in a building containing an assembly room and using a large number of lights. Where circuits are distributively interlaced, and a part or all of the lamps are easily turned on or off, only those wanted at any time and place need be used, and none will be left burning because to light them later would be too much trouble. The most economic as well as the most convenient design so places switches that at least a part of the lamps in a room may be turned on and off at every door of the room. It is thus unnecessary, as with one switch, to walk back in order to turn off the light, and there is less danger of its being left on in unoccupied apartments. In rooms where varying degrees of light are needed, and service is for fixed and regular periods, the designer can so arrange the groups of lamps that there may be rotation of use, thus keeping them in uniform wear and preventing contrast when all are burning. These are a few of the devices with which the expert engineer so equips his plans that, although the cost of installation may seem large, it is more than offset by satisfactory service and economic operation.

There are two general systems of interior lighting, the indirect and the direct. In the indirect system, the lamps are entirely concealed from view and their light is distributed by means of reflecting or diffusing surfaces. The installation of this system is costly, uniform distribution is difficult, and, as only about 50% of the incident light is utilized, the system is wasteful. In the direct system, the lamps are so placed that, although they may be seen, they are not in the usual line of vision. The installation by this method is less costly, and its operation much less wasteful, since nearly all of the light emitted does useful work. It also facilitates uniform distribution, and lends itself more readily to decorative effects and the expression of symbolism.

The accompanying Figs. from plans made in 1904 for the Westminster Church of Kansas City, may serve to illustrate the application of these principles to a case wherein the expenditure is to be moderate. The results are a good distribution of light and a satisfactory illumination in each room. All parts of the auditorium are visible; each seat receives a minimum of two candle-feet, and the variation is less than 20%. No more conclusive justification for the degree of control and lighting here provided for could be desired than the enthusiastic commendation of the parishioners, and the fact that the monthly bills for current at the rate of ten cents per kilowatt-hour, with the usual church services, and including current for organ motor, range from 15.00 to 23.20 dollars.

NOTES ON THE SPECIFICATIONS.

The following brief notes on the specifications will indicate the grade of work, and assist in explaining the figures.

The installation is three-wire with neutral equal to the sum of the outside wires, and with 104 volts on each side; the drop inside the entrance is slightly less than 2% with full load.

The interior fixtures are of brush brass, and those on the exterior are of black-finished brass or copper. All were specially designed to suit the architecture. Gas is used only for emergency lighting and for the kitchen range; this range is also provided with an outlet for cooking by electricity.

The entrance-switch, fuses, and Thomson wattmeter are mounted on slate bases in fire- and dust-proof box in basement.

All cabinets have white marble backs and sides, beveled plate-glass doors, trims of polished wood, and are set flush with finished walls.

Cabinet No. I is in the basement corridor and, in addition to fuses, contains five triple-pole, single-throw knife-switches; one to control each of cabinets II, III, and IV, one on feeders for future use in proposed assembly rooms in the basement, and one on feeders to supply lamps, not yet installed, for lighting the stained glass over the auditorium dome.

Cabinets Nos. II and III are in the south passage on the main floor, and in addition to fuses each contains 20 double-pole, single-throw knife-switches, 10 on each side of the system, controlling circuits supplying the ceiling outlets in auditorium, school-rooms, main entrances, vestibules, corridors, cloakrooms, young-people's assembly rooms and parlors. A pair of switches in each of these cabinets was provided for future use, one of which has already been put in commission for lighting the library and study hall on the second floor.

Cabinet No. IV is in the main corridor and contains cartridge plug-fuses to protect 16 circuits, 8 on each side of the system, supplying choir-rooms, organ-loft, pastor's study, kitchen, closets, boiler- and coal-rooms, brackets in auditorium, schoolroom, vestibules, corridors and parlors, attic, and lamps in all parts of the building intended for use at times when full lighting is not needed. In this cabinet, also, an extra circuit is provided.

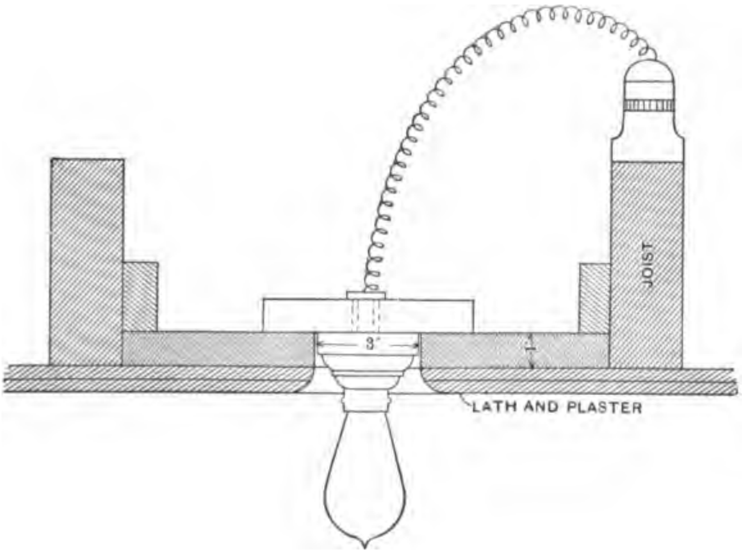


Fig. 2.

All outlets not controlled from cabinets Nos. II and III are controlled by " Diamond H " flush push-switches, all sockets and receptacles being keyless.

The elevation of ceiling outlets above floor lines range from 12 ft. in the parlors to 40 ft. for octagon at base of dome in the auditorium.

All lamps in any figure and in all figures in the same room are of uniform kind and candle-power. All lamps in auditorium ceiling outlets are clear standard Edison and all lamps in brackets are frosted spherical.

Lamps over pulpit platform (see outlet No. 6 on Fig. 1) being back of the pulpit arch, are not visible from the auditorium, and furnish over 2 candle-feet on pulpit, console, and music-rack.

The outlets in the ceiling of the auditorium are so constructed, Fig. 2, that lamps are drawn up into the attic for cleaning or renewal.

The bracket-lamps are used when light is needed only in certain places as for choir practice, janitor's work, pastor's study, etc., and are not a part of the general illumination, which is always from above.

In the wall and ceiling decorations, deep cream predominates; and the designs for all fresco work in the building have special reference to the location of lamps and the figures employed in their distribution.

Discussion on "Local Organizations," at Milwaukee, Wis.
May 30, 1906.

President Wheeler: The Institute has given a great deal of attention to the interests of the members who are located at a distance from New York. The proposed revised Constitution which was recently put before you, and which was not adopted, principally because a large proportion of the members did not think to send in their ballots, made some additional provisions for local organizations. I hope that in another year or two this Constitution, or something similar to it, will be adopted by the Institute. The summer conventions of the Institute are, as you know, held outside of New York, to bring us into closer contact with the members who live at a distance from that city. Our meeting held in Milwaukee this week is with that object.

We have a Committee on Local Organizations, and we have chosen as the chairman of that committee one of our past presidents who was particularly active and successful in developing the Institute along the directions which drew the local members into the parent organization. We will now have the report on that subject, and I have pleasure in introducing to you a distinguished past president of the Institute, Mr. Charles F. Scott, of Pittsburg.

C. F. Scott: The Committee on Local Organizations held a meeting three weeks ago at which it was decided to bring up the general subject of Local Organizations for discussion at this meeting of the Institute. There was an informal dinner last evening, at which representatives of local organizations were present. A general discussion took place, almost all of the twenty or twenty-five present expressing their views. In this way those particularly interested have had an opportunity to interchange ideas. I will endeavor presently to give a general summary both of the expressions of those present last night and also of those which have come in reply to a circular letter sent to the officers of the local organizations about a month ago.

I have found in my own mind a change of ideas regarding local organizations. The expectations and plans of a few years ago have been subject to modification as the subject has grown and the branches assumed a new relation to the Institute. The initial purpose was to provide means by which Institute members could get together locally, as a kind of adjunct to the regular work of Institute. It was difficult to lay out a definite scheme and plan of work, because conditions were difficult to foresee and were different in different places. I felt then that we were somewhat at fault in not being able to tell just how the work ought to be done, but now I believe it was wise not to prescribe definite plans, but to allow freedom for development. The branches are becoming an important organic part of the Institute, which makes necessary a change in our general policy.

BRANCHES AND INSTITUTE DEVELOPMENT.

Before entering into details and methods, let us first take a general view of the situation. The problem presents itself to the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS of dealing with a membership which in the last five years, since Mr. Steinmetz was chosen president, has grown over threefold, from approximately 1250 to 3800. How to get the best results for the engineering profession and the INSTITUTE as a whole on the one side, and for the individual member on the other side, is the problem now before us. It is a different problem now from what it was when our INSTITUTE began some twenty or more years ago. It is different because our membership is larger, because it is more widely scattered, and also because of the number of men in many different centers is becoming sufficiently great to enable these centers to begin a development of their own, to cultivate a self-sustaining interest and life in their local centers. This is something which was obviously impossible a few years ago. I need not discourse on the rapid development, quantitatively and qualitatively, of electrical engineering work in general, of the new lead it has taken in industrial and commercial life; the discussion on papers at this meeting shows how methods and apparatus which were known several years ago, but were not used to any extent, have within the past year or two received a new impetus, a new opening, a new opportunity, on account of this wonderful development. This is indicative of the new conditions which now confront us.

Here is our INSTITUTE, grown three times as large in five years. In the same time electrical industries, as measured by their output, or by the capital invested, have doubled. In five years more, if this rate of progress goes on, the industrial output will again be doubled, the demand for men will be doubled, our responsibilities as engineers will be doubled, and the opportunities and responsibilities of the INSTITUTE will be doubled. How shall we look forward to meet them? What new developments, what new kinds of work, what new methods, are to be adopted by our INSTITUTE, which have not been necessary in the past? It seems to me that considerations like these are the large and important questions of policy and method which lie before us unstudied It seems to me also that one method of meeting these new conditions is by a broadened and general activity among our membership, and that that activity can come largely through the medium of local organizations. Here are a dozen or twenty cities of considerable size situated here and there with large electrical interests, and electrical men increasing in numbers and ability. Electrical societies are soon going to spring up. These men are getting together There is a common interest which will be an attractive force drawing them together for social acquaintance and professional intercourse.

THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS has the opportunity of continuing to take the leadership by assisting in the cultivation and development of these local groups, and at the same time drawing unto itself a new strength by making itself a national aggregation of these many societies.

LETTERS FROM BRANCHES.

The recent letters received from branch officers indicate, both by their general tenor and their suggestions. the lines along which this work may be profitably developed. In these letters I have noted three things in general in addition to the discussion of specific topics.

First: the branches consider themselves a definite, established, integral part of the INSTITUTE. The question discussed is not whether branches should exist, but what relationship between the INSTITUTE and its branches and what methods will increase the effectiveness of their work.

Secondly: every local organization stands on its own merits; its success depends upon its own activity. In one letter it is summarized thus:

> The success of all the local branches will depend entirely upon the number, character, and ability of the men composing them.

Thirdly: It is recognized that the New York membership, by whatever name it may be called will, on account of the number and character of those resident in New York, continue to be the large and controlling factor in the INSTITUTE. This relationship is expressed in one report in this way:

> The entire INSTITUTE should be considered as made up of unit branches, each of the relative importanc it makes itself and each having proportionate representation and rights in the general management of the INSTITUTE. The parent organization should be the medium through which the efforts of the individual members may be transmitted to each other.

The views thus summarized show a prevailing sentiment which is significant. The branches are not merely experimental adjuncts, but they are representative of a large and substantial portion of the INSTITUTE membership, and are ready and anxious to share in its work and contribute to its success.

PAPERS.

It is the practically unanimous view that the papers and discussions of the branch meetings should be placed on the same basis of merit with regard to publication as the papers which are presented in New York.

Many branches find that original papers, either based upon the topics taken up in the New York meetings or entirely independent subjects, are preferable to the reading and discussion of the papers which have been presented in New York. Papers of local interest, sometimes when coupled with excursions, are found profitable.

A wide field is afforded by the branches for securing material for the INSTITUTE. One report says:

The greatest good can be obtained in the branch meetings by having papers on technical subjects by engineers who apply theory to practice in their everyday work.

These practical engineers are widely scattered, and practically the only way by which the INSTITUTE can secure contributions from many of them is through contributions to the branch meetings. A wealth of experience should be procurable in this way, which is not likely to come through the meetings in the metropolis.

LOCAL METHODS

Leaders: One report says:

There has been an excellent attendance and a live interest. I must confess, however, that the burden of the work has fallen on a few men.

The same confession could probably be made with regard to every branch and, in fact, to the operation of the INSTITUTE management. The work will always fall upon a few men, and success depends in a large measure upon the securing of right men as leaders and upon their activity. There must be an active leadership which can secure interest and coöperation from many busy men.

Subjects of Papers: The kind of material, whether INSTITUTE papers or original papers or topical discussions, must be determined by particular conditions. Subjects and methods which may be the best in one case are not useful in others. The success of a branch depends largely upon the discretion and judgment exercised in the laying out of the programs. In some cases a division of the work of arranging for meetings has been made, by which different members of the executive committee take charge of particular meetings. The definite placing of responsibility and, to some extent, the rivalry which results is found to be stimulating.

Much depends upon the snap and tact of the presiding officer in making the meetings attractive and interesting. Occasionally a man of dignity and reputation is chosen, who lacks interest and enthusiasm. I am inclined to think that the latter qualities are more important than the former.

Social Functions: Occasional dinners or the serving of light refreshments after meetings, or visits to electrical or other installations are found to be helpful in various places.

Such matters as regularity of meetings, and attractive and explanatory notices of meetings to be held are hefpful in sustaining a definite interest.

RELATION TO INSTITUTE MANAGEMENT.

Several suggestions are made by which the management of the INSTITUTE may be made helpful to the branches and they in turn may be useful to the INSTITUTE.

Papers Committee: A close relation between the papers committee and the local secretaries will enable an exchange of suggestions of topics and of authors. If a given topic is taken up in a number of places it will draw from many sources.

Affiliation with Other Societies: The INSTITUTE branches should be the local electrical societies, making unnecessary other electrical organizations. They should coöperate with local engineering societies, often taking the general relationship of electrical sections in them. The holding of electrical meetings which all members of the local society may attend may be found ample compensation for the use of the society's rooms as a meeting place.

Visits. Personal visits to the branches by officers or representatives of the INSTITUTE or by lectures should be extended Such visits have been found quite stimulating to a number of the branches. The labor and expense involved make this difficult to carry out on a comprehensive scale. On the other hand, if attention be given to the matter it will be practicable to make a number of appointments, particularly through the agency of members who are traveling.

The routine management of the INSTITUTE's affairs have in the past not taken much account of the branches. They however, have developed and afford an opportunity for the administration of the INSTITUTE upon a broader basis. The best ways and means for carrying out this new relationship must be developed by experience. The income of the INSTITUTE does not justify a very large expenditure on account of the branches. The dues were fixed before the formation of branches was contemplated. Such matters as club features, reading rooms, refreshments, paid lecturers and the like, may be very desirable, yet the INSTITUTE treasury certainly cannot be called upon to meet expenses other than ordinary " meeting " expenses.

University Branches: The meetings in universities meet with quite a wide variety of conditions. In some the INSTITUTE meetings are substantially an organic part of the educational system; in others they are of less moment, precedence in certain institutions being given to local electrical or engineering societies.

In general our electrical professors regard the local INSTITUTE meetings, and the connection of their young men with the INSTITUTE as members of its student class, as profitable and stimulating, particulary as it awakens a definite interest in practical engineering affairs.

Professor Norris, of Cornell University, a member of the Local Organization Committee, reports as follows:

> The results of the Ithaca work during the present year have been satisfactory indeed. The discussions have been animated and helpful and the branch is recognized as an important aid in our educational work. The presence of the branch greatly stimulates interest in the INSTITUTE, which is evidenced by the number of applications for associate membership and student membership sent in from Ithaca. Our plan is to distribute advance copies before the meeting and to assign the presentation of the papers to students or members who have had experience in the field covered by the paper. A feature which we have found useful is to present biographical sketches of the writers of the papers.

A report from the University of Wisconsin shows that the meetings have been well attended and a considerable interest developed. The attendance has been greater than in former years.

From these and other reports the value of the relationship between the universities and technical schools and the INSTITUTE is shown to be well established. The principal problem in this work, as in that of the regular branches, is in the selection of methods which are best applicable to the particular conditions and to carry on the work in such a way as to make it live, interesting, and profitable.

FUTURE PROSPECTS.

There has never been an occasion in which the two elements, the officers of the INSTITUTE on the one hand, and the representatives of the Branches on the other, have ever gotten together as they did last night. In a measure I combine the two. I have been closely identified with the New York management, and I am also not a New Yorker, and have the outside point of view. But some of my New York friends have had the strictly New York view; they have not appreciated the point of view of the man outside of New York. On the other hand, the men in the branches have not seen some of the administrative difficulties; they have not had quite the view of the outside work as a whole which they should have. There has been something of misapprehension, something of criticism, now and then, which is a condition which will be removed when the two sides get together and talk it over as they did last night.

There is apparent on both sides, among the men from the outside and among the officers from New York at this time, a firm conviction that the branches constitute one of the strong elements of the INSTITUTE which must be fostered and developed; that the means of carrying this out and the methods which should be used are hard to prescribe, and must be worked out one by one as a matter of development or evolution. I believe we have now, as we never had before, the conviction that the time is ripe for the branches, that this is the broad policy upon which to develop the INSTITUTE, and also the determination on both sides to work it out along the very best lines.

These, then,are some of the elements of general policy: first, that the branches must be self-reliant; secondly, that the branches must be an important, recognized part of the INSTITUTE, making it in fact as well as in name a national organization; and thirdly, that the future methods of the INSTITUTE must be such as to carry out these ideas, to help the individual branch as an individual thing and to incorporate into it an important feature of the work of the whole INSTITUTE, so that the branch itself can profit from the INSTITUTE, and so that the INSTITUTE as a whole can get the best results from the strength which comes from its branches. These are the general lines of policy upon which I think all are substantially agreed.

George O. Squier: There seems to be no doubt as to the value of the branches, and the question is as to the method of carrying out the suggestions for improvement. I was far enough away in California to have an outside view of the matter. About a year ago an attempt was made to start a local organization. We all knew we had plenty of material there, men who rank high in the engineering profession, but we had peculiar circumstances to meet. We had two rival universities close together, and each of them in close proximity to the city, and we had other men who had been connected with the universities and were at the time connected with commercial organizations, so that on the whole, for some reason not clearly definable, the branch in San Francisco was not started as early as it might have been. About a year ago, as I remember, the matter was agitated, and post-cards were sent around to get the views of the men who might be interested, and we were surprised to find the number of people ready to cöoperate. A hall was given us, the Mechanics Institute Hall in the Library Building there, and the meetings began, and it was really surprising to find how beneficial they were. We found the monthly meetings afforded an occasion for not only studying the TRANSACTIONS of the INSTITUTE, but of preparing something definite to present at these meetings, and thereby getting the opinions of good men, which we all wanted on certain subjects, and which we would not get otherwise.

These were forwarded, of course, to the Secretary, and some of them have appeared in the PROCEEDINGS of the INSTITUTE. Another feature was that the engineering students of the universities came into our branch in comparatively large numbers, so we started these young men who intended to make the profession their life work, we got hold of them early in life, they learned what the INSTITUTE is, and they got acquainted with some of the men high in the profession, and altogether it was a very successful affair.

Another feature was that it encouraged original ideas. The members were induced to present ideas which would not have been brought out had there not been some occasion of that sort. We started with practically no rules; we thought we would allow the matter of rules to develop. I think that is an excellent idea, not to have too many rules, in fact very few, as circumstances vary in different parts of the country. We found people would bring out their experiences in one branch or another of the profession, and some of the discussions were excellent.

Up to the time I left there about a year ago, the attendance was large and the whole matter was considered by every one as a perfect success. I believe that in view of the recent disaster things have had a temporary setback, but I have no doubt the work will be taken up and will be continued, and I for one, from personal experience, know the value of these opportunities to get into touch with the parent institution. If you are kept for several consecutive years outside of New York, you find the PROCEEDINGS coming in year after year, but the distance away from headquarters tends to lessen the general interest in these things, but you find there is very much interest in having a meeting and discussion at some definite place and time. As far as my individual experience goes, I testify to the great success and value of this sort of thing, and think it is one of the greatest objects we have or can have in view, and that is to nationalize this institution by a more vigorous coöperation among the branches.

Kempster B. Miller: I am a great believer in local branch work and have had much opportunity to study it. I have been actively connected with the committee in Chicago for four years, and chairman of it for two years. I believe that I can say our work in Chicago is successful. We have good attendance, usually over 100, and lively discussions are the rule.

In regard to the kind of man at the head of a local organization, I think reputation *per se* has little to do with it. The proper kind of man is the busy man. It is my experience, after four years' work, that it is the busy men, the men who ought to be doing something else, who have given us the best work on the committees.

Local branch work involves a great deal of work on a few men. That makes me believe that the committees as a rule are too large. I think ours in Chicago is too large. I think five good, strong men would make an ideal committee.

Our plan in Chicago has been to have the committee meet occasionally at luncheon, when we could all spare a little time, to talk over the program for the next meeting and to delegate to two of our members the responsibility of arranging for each meeting and making all necessary provisions regarding it. In that way we have somewhat minimized the labor and also secured definite responsibility for each meeting.

The greatest fault I see in the present method of handling the branch work is the lack of any sort of real coöperation between the branches and the main organization. I do not put the blame or lack of coöperation anywhere. I am willing to take a good deal of the blame myself; but I believe that if some method could be had whereby the men in charge of the local branches could feel that they were part of the big organization, not only in name, but in fact, it would result in great good.

I do not believe our branch in Chicago needs " nursing," to apply Mr. Scott's term, but I do think that when any number or group of people are trying to further the interest of a great body, they can do a great deal better work if they all pull together. I believe one good way to bring about this coöperation would be to have a representative in every important branch at least on the Committee on Papers. I think that would give an important working connection between the organizations. I think also it would be well to have some good committee in New York, with perhaps an assistant secretary, to take up with the various branches in a suggestive way, an advisory way, and above all things in a helpful way, the work which the various branches are doing.

C. P. Steinmetz: From my experience with local branches, and as a result of listening to the discussion, I believe there are two classes of local branches, educational branches and originating branches. Some of the very active branches are mostly engaged in educational work, and closely connected with universities. Their work consists in reading and discussing our papers with the students, using them for educational purposes, and they are related to the INSTITUTE as a feeder of the membership; they are interesting the students and the local engineers in the INSTITUTE, and inducing them to join it. These branches rarely have original papers read before them, and it is not the purpose they are aiming at. A representative of these branches on the Committee on Papers would be of less utility, and would hardly be asked for. The other class of branches are those which read papers of their own, more or less original. These branches are of the same character as the Institute at large do the same class of work, only to a lesser degree in quantity, though not quality, in accordance with the lesser number of members. These branches may well be put on a certain equality with the New York branch by giving them representation on the Committee on Papers, or, what I should consider preferable, by permitting these branches to have a local committee on papers and giving this local committee on papers power to correspond with and be represented in the national committee on papers.

There is one more feature which might well be considered, which I have not heard referred to, and which appears to me of importance in establishing the relations between the local organizations and the national body more closely. By the Constitution it is required that the vice-presidents should be distributed geographically. This has not always worked out well and is difficult to do, because a quorum of the Board of Directors is required at the meetings which are held in New York. The chairman or delegate of every local branch should be informed of every meeting of the Board of Directors and should have the right to be present at the meeting of the Board of Directors, have no vote, but merely the right to consult with the Board of Directors. In this connection I believe it might not be a bad scheme to extend representation in the Board of Directors, as consulting members without vote, to all the past presidents of the INSTITUTE. The Board of Directors, which is the central executive and administrative body, should be in more continuous and close touch with the past history of the policy of the INSTITUTE as represented by the past presidents, as well as with the present history of the INSTITUTE at large, as represented in its local branches, by having representatives of both on the Board for consultation. The INSTITUTE is growing so large and important, that something of this kind appears to me desirable. I do not believe you can establish rigid rules for the local branches, but must let the local branches work out their own salvation; but in this direction a very flexible committee on local branches in New York City, with considerable power, would very greatly assist the local organizations. The different experiences with different branches appears to me due to largely those two main characteristics; a meeting in Philadelphia and a meeting at the Wisconsin University, while of the same intellectual standing, are inherently different in character and class of the work they do, and their organization and relation to the national body must therefore also be different, and different again must be the local organization in a place such as Schenectady, which essentially represents an electrical manufacturing company. You cannot make rigid rules to cover all these cases.

Samuel Sheldon: I think it is conceded by all that we have the success of the INSTITUTE at heart and, as suggested by Mr. Miller, the advance of its interests can best be accomplished by coöperation between the local organizations and the central executive board, which, by accident, happens to be in New York.

Now, in order best to coöperate, we should consider what the elements of the success of the INSTITUTE are. From various criticisms and suggestions it appears that the success of the INSTITUTE is variously considered by various minds. Some consider that a large excess of income over outgo determines it; others that a large volume of transactions is representative of success, for each member gets more in return for his dues; another class considers that superior quality of transactions, giving great prestige, is the element of success which is of the greatest importance. I consider that the social and instructional element is also of great importance. Another element which we all appreciate is the size and comprehensiveness of our membership. Concerning the number of members of the INSTITUTE, when the local organization movement had its resurrection under President Scott, he expressed the opinion, in his opening address, that the potentiality of our membership was 25,000. He may have been too enthusiastic; he may have been correct. At any rate, that figure is much larger than our present membership, which is approximately 4000. The local branches can greatly assist in increasing the roll of membership. They know of those who reside in their districts, the ones that are eligible as associates, and they can persuade these gentlemen, if they will, to join the INSTITUTE. If our present members would each one bring in a single new member during the coming year, next year we could boast of 8000 members, and in a short time we would have our full complement.

As concerns the income of the INSTITUTE, there are two things that the local organizations can do. They can attend to their financial obligations to the INSTITUTE and they can ascertain the INSTITUTE requirements for transfer from Associate to Membership, one of which entails an increase in dues, and they can for themselves determine whether they are qualified for transfer. Should they find such to be the case, and should they merely communicate this fact to the Secretary, giving what evidence they have to sustain their positions, there will be no difficulty in their being transferred. There seems to be a great misunderstanding on the part of the members as to the work of the Examining Board. If Associates, who have in mind making application for transfer to the grade of Member, would carefully read over the INSTITUTE requirements, they could from these settle for themselves without any difficulty all questions as to eligibility. The duty of the Board of Examiners would then be largely of a clerical rather than of a judicial nature.

The determination of the bulk of the TRANSACTIONS, and the quantity of material which is to be published, is a question of policy. It can be made larger if it be desirable within reasonable limits, that are dictated by cost, or it can be made smaller. The quality of the subject matter in the printed publications of the INSTITUTE is a very important factor. The local organizations can assist in improving that quality by corraling the talent in their vicinities. The Constitution, as I read it, in connection with the By-laws, limits the membership of the Committee on Papers to five. The number of volunteered papers read before the INSTITUTE is about 10 per cent. of those presented; that leaves 90 per cent. to be secured upon suggestion and invitation from the Committee on Papers. Having a membership of only five, and a necessarily limited acquaintance with the profession at large and with individual abilities, it can be seen how the committee is hampered by the conditions under which it is forced to act.

Consider this other element which may be called social or instructive; as we nurture our children and instruct them when they are young and before they take hold of the heavy battles of life, and as we advise them in their later problems and studies, so it is desirable that our great and growing mass of younger members should be nurtured and advised. A proper sphere of activity of the local branches is to instruct, advise, and encourage; and a great deal of material which none of us would care to have published in our TRANSACTIONS can be locally presented and yet be of great value to the younger members.

It seems perfectly feasible and not very difficult to arrange so that the papers and discussions of the local branches shall receive the same editorial treatment as those occurring at New York or at the annual conventions; to arrange an equable distribution of the expenditures, after deducting publication, executive, and reserve expenditures; and to arrange for the local original presentation of papers from our best contributors.

Inaugural Address presented at the 209th Meeting of the American Institute of Electrical Engineers, New York, Sept. 28, 1906.

THE WORK OF THE INSTITUTE.

BY SAMUEL SHELDON, *President.*

At the last convention, held in Milwaukee, the question of the work of the branches of the INSTITUTE and their relations to the executive offices in New York revealed the fact that there was considerable lack of information concerning the scope of the INSTITUTE work and the method of carrying it on. The growth of the INSTITUTE as a National organization and the extension of its usefulness to its membership is so largely dependent upon the intelligent coöperation of the local organizations that it seems desirable that all should be familiar with its work.

SECRETARY'S OFFICE.

The Secretary is the executive officer of the INSTITUTE and has charge of all of its routine work. Because of his familiarity with all phases of the work, he is being constantly called into conference with the officers and committee men over questions of policy, ways and means. He receives many calls from members visiting New York, and is often able to assist and give valuable advice and introductions in furtherance of professional purposes. This is especially true in the case of members coming from foreign countries. In carrying on his work, except that which he is, by the Constitution, required himself to perform, he has the assistance of a staff of six assistants besides an editor and a bookkeeper. The character and amount of routine work done during the year ending April 30, 1906, is indicated by the following:

INSTITUTE OFFICE STATISTICS FOR YEAR ENDING MAY 1, 1906.

During the year there were 9802 letters received, entered, and filed, and more than 4000 written. There were 2760 changes of address made in the catalogue, directory, mailing-list and card-index. This indicates that the addresses of more than 70 per cent. of the members were changed during the year.

The number of bills rendered was 5928, items of remittances received, 4858; bills received and checked, 825; checks and warrants drawn, 338.

There were 572 applications for election received, and in connection therewith, 1716 endorsement forms were issued, of which 1638 were returned. The number of applicants for transfer was 53, involving the forwarding and return of more than 600 inquiry forms for the consideration of the Board of Examiners.

Seven editions of monthly announcements, aggregating 96 pages, were prepared and distributed.

Numerous notices and circular letters were prepared, printed, and distributed to the membership. These related to a variety of subjects, such as INSTITUTE meetings, convention, proposed revision of the Constitution, proposed law regarding the metric system, invitations to visit Europe from our sister societies in England and Italy, and other INSTITUTE business.

The number of pages of engineering papers and discussions edited and proofread for publication in the TRANSACTIONS, was 1138. In connection therewith 91 half-tone, 196 wax, and 68 zinc, engravings were made. In addition to the above mentioned engineering papers, there were about 250 pages of current INSTITUTE news prepared and published in the monthly PROCEEDINGS, and not included in the TRANSACTIONS. More than 54,000 copies of the INSTITUTE PROCEEDINGS were mailed; 60,250 advance copies of engineering papers were printed and distributed.

The cost of the year's work, for the TRANSACTIONS, salaries, postage, express, stationery, printing etc., was $40,767.22, or $10.48 per member. The total receipts per member during this period were $12.97, and therefore five-sixths of the receipts were disbursed in the interests of the membership at large, irrespective of location.

THE BOARD OF DIRECTORS.

The Board meets regularly once a month and performs the duties customary with such a body. It makes appropriations, approves bills and recommendations from committees, and determines and outlines broad questions of policy.

The Constitution authorizes the appointment of an Executive Committee of seven members to which the Board may delegate certain of its powers. This provision was made to enable the INSTITUTE work to go on in case a quorum of the Directors could not be obtained. However, the Executive Committee has had but few meetings in several years, because of the large attendance of the Directors, and their great interest in the INSTITUTE work. The members of the Board are as a rule quite familiar with details. Their attendance is probably due not only to their immediate interest in the INSTITUTE work, but to the fact that the meetings offer an opportunity for professional intercourse between its members. With a wider geographical distribution of the membership of the Board, it might in the future seem desirable to make greater use of the Executive Committee, but one or two meetings per year of the full Board being held. Under such circumstances it might seem advisable to furnish free transportation to the members coming from a distance.

As is usual in similar organizations, much work is performed by committees under the immediate direction of their respective chairmen. The general character of the work of these committees, and some of the problems which they are endeavoring at present to solve, follow:

THE BOARD OF EXAMINERS.

This board receives from the Secretary all applications for membership, or for transfer, passes upon the qualifications of the various applicants, and makes recommendations to be acted upon by the Board of Directors. The requirements for election as an Associate are so easily fulfilled that only about 2% of the applicants fail to qualify.

The requirements for transfer to the grade of Member are specifically stated in the Constitution, and it is desirable that a high standard should be maintained. It seems as though applicants for transfer could readily determine for themselves, from a perusal of the Constitution, whether or not they are eligible for transfer to this higher grade. A large portion of the labor of this committee is due to the loose and indefinite manner of filling out the specification papers on the part of the applicant; and the tendency to refer to members of professional eminence, or those prominent in INSTITUTE work, rather than to members who are familiar with the applicant's career and who are competent to corroborate the statements made in his application. Careful reading of the Constitution and By-laws; definiteness in filling out the application blank, and proper selection of references, will facilitate the work of this committee, and materially reduce the time necessary for transfer.

THE COMMITTEE ON INCREASE OF MEMBERSHIP.

The removal of the Executive Offices to the new Engineering Building will entail an increased expenditure for carrying on the INSTITUTE work. To provide for this, the simplest method seems to be to increase the membership. The Secretary's staff is able, with slight additional expense, to take care of twice as many members as we have at present. The increase of expenditure incurred by the increase of membership will be due to an increase in the number of TRANSACTIONS, of printing, and of postage. The enormous annual growth of the electrical industries is accompanied by a similar increase in the material available for membership; and the figure of 25,000 possible members given by President Scott in his inaugural address, seems by no means to be extraordinary. While in recent conference with a member, concerning the make up of a committee, of the several names suggested as suitable for appointment, one half were not to be found in the INSTITUTE directory. The small number of members in some of our states, to which President Scott called attention, has not been materially increased. Perhaps this is due to the fact that persons eligible for membership are engaged in the operation of plants of but medium or small size, and that in our papers and discussions sufficient attention has not been given to this kind of work to stimulate their interest and warrant their enrolment. One of our foremost and largest universities, with an electrical engineering course in its curriculum, has not a single person connected with it whose name appears upon our rolls, nor does its library subscribe for our TRANSACTIONS; on the other hand, another of our large universities has connected with it 22 Members and Associates. This committee is about to take active measures to bring to the attention of non-members the advantages to be obtained from membership in our organization.

THE COMMITTEE ON TELEPHONY.

Complaints have been received from members engaged in telephone work, that not sufficient attention has been given in the past to this subject; and in some cases resignations have been threatened for this reason. It is true that the number of papers presented on this subject has been few, although those presented have been by the most eminent authorities, and some of them have been classic in character. This committee will take measures to increase the usefulness of the INSTITUTE to this art, by arranging for meetings on this subject, designed to bring out discussion from members who are too busy to prepare papers, these meetings to be held at various branches instead of at New York. It will also assist the preceding committee in widening our membership in telephone circles.

THE COMMITTEE ON LOCAL ORGANIZATIONS.

A marked increase in the usefulness of the INSTITUTE cannot be accomplished except through the coöperation of the executive committees of the branches. It is therefore desirable that the branches should be well organized, and that their work should be carried on in a manner as efficient as possible. It seems desirable that in most cases their executive committees should be made up of but five members, and that the time of their election should be shortly after the regular INSTITUTE election, to enable them to make preparation for active work when the INSTITUTE year starts in September. A larger committee enables the members to shift upon each other's shoulders the responsibilities for good branch work, which results in a lack of coördinated effort. The exceedingly attractive program of the Schenectady Branch for the coming season has, however, been arranged by a committee of nine. The branches should be in constant communication with the Secretary's office, not simply that the progress of their work may be known, but so that they may give and receive suggestions with a view to attaining a greater efficiency. The branches can be of great assistance in increasing the membership by exerting organized efforts in the localities of which they are centres. They can, without undue loss of dignity, from immediate knowledge suggest to Associates in their vicinity the desirability of making application for transfer to the grade of Member. The transfer, it is true, means slightly increased dues; but this slight additional cost is more than compensated for by the prestige resulting from the official recognition of the applicant's professional attainments and standing by the INSTITUTE's Board of Directors.

Furthermore, such slight additional expense is but a small matter to such members; and it is their duty to the organization which represents their profession to enroll themselves in its advanced grade.

Interest in the branch meetings will be hard to sustain if the programme consists chiefly of papers that have been previously read in New York. It is very desirable that original papers should be presented, and that local talent should be brought to the front. Efforts should also be made to obtain original papers from men eminent in our society, but who live at a distance. This has been done with marked success in some branches and discussions of great value have been drawn from those in attendance, but from whom formal papers could not be obtained without great difficulty. Arrangements will be made in the future to publish the best of these papers in the TRANSACTIONS.

Experience shows that eminent engineers coming from a distance take great pains to please their audiences, and are rewarded, encouraged, and helped by the sympathetic attitude of their listeners. Lectures or instructional papers, by local members of expository ability, dealing with prior art and conditions, underlying theory, or present standard practice, are of particular value to younger, rising members, and properly find a place in the branch program. It is also desirable that an annual calendar, including the dates of future branch meetings, should be made up, to enable the Secretary's office to coöperate with the executive committees of the branches. All this work of the branches will be coördinated and assisted through the efforts of the Committee on Local Organizations.

THE COMMITTEE ON HIGH-TENSION TRANSMISSION.

The results of the work of a committee thus designated, published during 1902-3, proved of such great value that they were reprinted and bound in a single volume under the auspices of a publishing company in coöperation with the INSTITUTE, and placed upon sale so as to be accessible to the public. In view of the many systems installed since that time, and the large number of proposed systems for transmission over much greater distances than ever before, which will use increased voltages, involving many difficulties of insulation, of protection, and of construction, the reappointment of a committee for this work has been deemed advisable. The meetings arranged by this committee will be held at interior points in order to insure wide representation, large attendance, and full discussion.

THE LIBRARY COMMITTEE.

This committee has a great deal of work in hand. Besides installing and systematizing our present library in its new quarters, some organization for coöperative management in connection with the libraries of the Mining and the Mechanical Engineers should be effected. By the Constitution, this committee is required to direct the expenditures for the furnishings which will be required in the new executive offices. In the past the library has been but of small use to the members not residing in New York and its vicinity. It is expected that in the near future arrangements will be made by which distant members can obtain lists of publications on desired subjects, abstracts, and translations for a nominal fee. This committee will also prepare an authors' and subject index of the TRANSACTIONS, in which will be included the papers presented at the International Electrical Congress, held at St. Louis in 1904.

To meet adequately the requirements of the membership represented by the United Engineering Society, extensive additions should be made to the existing three libraries. Competent authorities have considered this question, and have concluded that there should be an immediate expenditure of $125,000, and a fund which would provide an annual income of $30,000 to be expended for maintenance and operation.

THE COMMITTEE ON BIBLIOGRAPHY.

This committee expects to have in press by next December a chronologically arranged, annotated bibliography of the Wheeler Gift. In addition to the main bibliography of books and periodicals there will be appendices covering a great part of the pamphlet literature, including parliamentary papers, patents and litigation, trade catalogues, prospectuses and reports on projected undertakings in telegraphy, cable and telegraph tariffs, and instructions to operators as to the care and use of instruments, and extracts cut from periodicals not devoted exclusively to electrical subjects. The book will contain about 500 pages. Its preparation has entailed a great deal of labor, and the manuscript has been critically examined at the British Museum, in the libraries of several of the European electrical associations, and in our own Congressional Library.

THE EDITING COMMITTEE.

This committee, upon which rests the responsibility of the publications of the INSTITUTE, has in the past been burdened with a mass of correspondence and critical reading which it is unfair to expect without compensation. There is no valid reason why the responsibility should not be delegated to the

Editor and the labor be performed in the Secretary's office. Furthermore the services of this committee are needed in other directions. The monthly PROCEEDINGS, because of the character of its contents, appears irregularly and frequently remains unopened or unread upon its receipt. This condition should not be allowed to persist. Every number should contain such fresh, interesting and valuable material as to excite curiosity and command the immediate attention of him who receives it. It should be the official organ of the INSTITUTE in fact as well as in name. Its ephemeral portion, besides containing the announcements from the Executive Offices, should contain news concerning the individual members and the branches.

The Editing Committee will consider this matter with a view of not only making the PROCEEDINGS more attractive but of increasing its value as an advertising medium.

THE COMMITTEE ON STANDARDIZATION.

Professor F. B. Crocker and Mr. C. O. Mailloux of this committee represented the INSTITUTE at a meeting held recently in England in which ten nations were represented. An organization of an International Electrotechnical Commission was effected in which the INSTITUTE, as representing the United States, will be entitled to one vote. This commission will probably meet during the coming year. This committee also has in hand the rearrangement and reclassification of a report which was presented, in a preliminary form, at the last convention of the INSTITUTE.

COMMITTEE ON NATIONAL ELECTRIC CODE.

This committee will continue to look after the interests of the INSTITUTE in the meetings of the National Conference on Standard Electrical Rules and the Underwriters National Electric Association.

THE COMMITTEE ON LAW.

This committee considers the legal aspect of actions about to be taken by the Board of Directors, interprets the Constitution and By-laws, and makes recommendations concerning their amendments.

THE COMMITTEE ON PAPERS.

This committee, besides carrying on the usual work of arranging for meetings and directly soliciting papers, expects the coöperation of the executive committees of the branches and of the Committee on Local Organizations in its work. With this assistance it expects to present an attractive program.

THE COMMITTEE ON FINANCE.

The direct supervision of the financial affairs of the INSTITUTE is entrusted to this committee, approval of all bills for payment and recommendations as to the investment of funds resting with it. The financial arrangements attending the removal of the INSTITUTE offices into the new Engineering Building and the details of the adjustment of our financial relations with the United Engineering Society will be considered by this committee.

THE BUILDING FUND COMMITTEE.

As a result of the admirably directed efforts of this committee $132,000 has been raised; of this $94,000 has been paid and $38,000 is in the form of time-pledges. It is hoped and expected that when the new building is formally given over to the United Engineering Society during the coming year, the whole amount of $180,000 due from our INSTITUTE will have been raised. The architect a few days ago stated that the building will be ready for our occupancy on Dec. 1, 1906.

This building is bound to become a center of activity which will help to shape the destiny of our nation. The present remarkable epoch which Mr. George S. Morison states is characterized by "the manufacture of power," is due primarily to the professional activities of the members of the three founder societies whose representatives form the holding and administering corporation known as the United Engineering Society. Our work does not end here. Having brought about this condition, it now rests with us to control it. On us, then, rests largely the responsibility for the overcoming of the short-sighted and selfish extravagance in the use of our natural resources so recently commented upon by Mr. James J. Hill. The immediate future, prophetically described by Mr. Hill, with its expensive fuel, its scarcity of iron, and its large population will demand from these members a more efficient transformation, transmission, and utilization of our supplies of stored energy, and a more extensive use of our immediately received energy. The new Engineering Building stands for the fulfilment of this great purpose.

A paper presented at the 209th Meeting of the American Institute of Electrical Engineers, New York, Sept. 28, 1906.

THE EFFECT OF IRON IN DISTORTING ALTERNATING-CURRENT WAVE FORM.

BY FREDERICK BEDELL AND ELBERT B. TUTTLE

INTRODUCTION.

It is well known that in a circuit containing no iron an impressed sinusoidal electromotive force will cause a sinusoidal current to flow, the current lagging behind the impressed electromotive force by an amount depending upon the relative values of the resistance and inductance, which in this case is constant. Assuming inductance alone in the circuit, the sine current which flows lags 90° behind the sine electromotive force and represents no power, the power-factor (cos 90°) being zero.

It is also well known that if the conductors of the circuit encircle iron, the inductance will no longer be constant. The current resulting from an impressed sinusoidal electromotive force will no longer be sinusoidal, but will be distorted and consist of a first harmonic or fundamental sine current of the same frequency as the electromotive force, and harmonics of 3, 5, 7 etc. times the fundamental frequency.

One of the first studies of this subject was made by Ryan and Merritt* who, from experimental curves of current and electromotive force, determined the hysteresis loop for the iron of a transformer. Steinmetz[1] taking certain hysteresis loops and assuming a sinusoidal electromotive force, has determined the complex current wave for a large number of cases.

The purpose of the present writers is to study more fully the relation between the harmonics introduced by iron

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* TRANSACTIONS, A.I.E.E., Vol. VII., p. 1.

[1] Steinmetz: Alternating Current Phenomena, Chap. X.

into the current wave, and the hysteresis loop of the iron to which these harmonics are due. For example, it can be shown that certain harmonics, defined by their amplitude and phase with reference to the fundamental, can be produced by iron; others can not, these latter being excluded as impossible by the determination of some physical limitation. The condition that hysteresis in iron causes it to absorb rather than to give out energy, at once renders certain harmonics impossible. The fact that the current can have a maximum value only coincident with the maximum value of induction in the iron is likewise a limitation. Again, the fact that after saturation the permeability decreases with the increase of the induction is a further limitation.

In case of a sine electromotive force and a complex current wave due to iron, the harmonics in the current wave (being 3, 5, 7, etc. times the frequency of the electromotive force) can represent no power.[2] Any power must accordingly come from that part of the complex current wave which is of the same frequency as the electromotive force. If this current lagged 90° behind the electromotive force, as it does with no iron present, there would be no power, as has already been pointed out. But the current of fundamental frequency is shifted ahead by an angle, ψ, of hysteretic advance due to the iron, so that it lags less than 90° behind the electromotive force; consequently it represents power, this being the power expended in hysteresis.

The current of fundamental frequency which we are to consider might be taken either as the *fundamental* sine curve, as we analyze the current into components of 1, 3, 5 times the frequency; or, as the *equivalent* sine curve, which is a sine curve equivalent in its effect to the fundamental and higher harmonics combined. The distinction between the fundamental and equivalent sine curves, which have sometimes been confused, will be taken up more fully later.

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[2] A symmetrical hysteresis loop introduces odd harmonics only. Taking $e = E \sin \omega t$ and current i, the work done per cycle is

$$W = \int_0^{2\pi} e\, i\, dt.$$

For any odd harmonic of n times the frequency, $i_n = I_n \cdot \sin n \omega t$. With this value substituted for i, the integral vanishes and $W = 0$.

A relation will be sought between the hysteresis loop for any iron and its angle of hysteretic advance.

Finally, consideration will be given to the effect of hysteresis upon the vector representation of alternating currents, and it will be shown that the complete diagram in any problem can no longer be drawn in a plane.

EFFECT OF THIRD HARMONIC.

From Faraday's law, $e = -\frac{d\phi}{dt} = -A\frac{dB}{dt}$,

it follows that if the electromotive force* impressed upon a coil be sinusoidal, the magnetic flux threading the coil will likewise be sinusoidal, and in phase 90° behind the electromotive force. This is true whether the coil embraces iron or not.

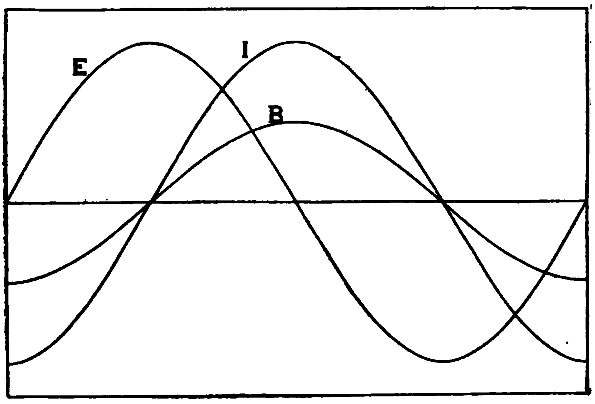

FIG. 1.—Sinusoidal current I and induction B, lagging 90° behind the sinusoidal electromotive force E when no iron is present.

If the coil does not embrace iron, the current likewise is sinusoidal and 90° behind the electromotive force; the flux is in phase with the current, and proportional to it. See Fig. 1. We may then write

$$e = -A\frac{dB}{dt} = -L\frac{di}{dt}.$$

The inductance L is constant; and hence the induction B is proportional to current i and magnetizing force H, permeability

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* Not including ohmic electromotive force.

being constant. The hysteresis "loop," plotted between B and H, becomes then a straight line.

With iron present, inductance and permeability are not constant. The induction B is no longer proportional to the current i and magnetizing force H, and with induction B sinusoidal (due to sine impressed electromotive force), the current i is not sinusoidal, but distorted as in Fig. 2. Since B and H are no longer proportional; instead of a straight line we have the hysteresis loop representing their cyclic variation.

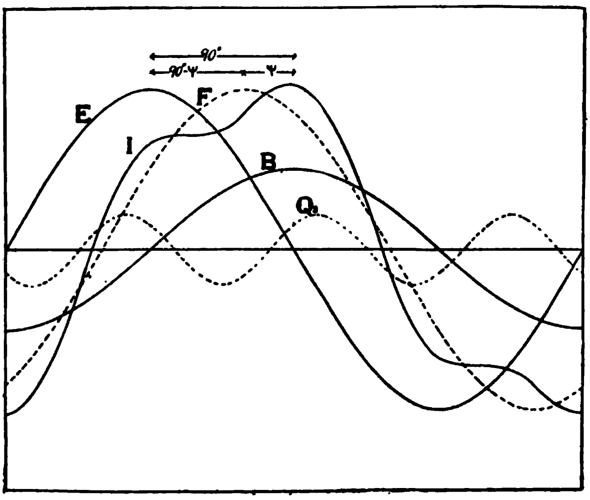

Fig. 2.—Complex current I and induction B with maximum values 90° behind sinusoidal electromotive force when iron is present. The fundamental (F) sine curve of current lags $(90-\psi)$ degrees behind E.

In the following work we shall deal with the fundamental and third harmonic only. The process will be to assume successively definite relative amplitudes and phase positions for these and build up the complex current wave. From this complex wave of current and the sine wave of flux, the hysteresis loop which would cause such a current is determined.

The equation for the current is

$$i = \sin \omega t + \beta \sin (3 \omega t + \theta).$$

The amplitude of the third harmonic is β (taking the fundamental as unity) and θ is its phase-angle, $+\theta$ indicating an advance, and $-\theta$ a lagging of the origin of the harmonic relatively to the origin of the fundamental.

Let us take a typical case represented in Fig. 2. The assumed fundamental and third harmonic of the current are represented by dotted curves. Here the amplitude of the harmonic is taken to be $\beta = 0.22$ (the amplitude of the fundamental being unity) and θ is taken to be $+45°$. The maximum of the current wave necessarily coincides in time with the maximum of the induction (for in a hysteresis loop the maximum H coincides with the maximum B). The sinusoidal flux, in accordance with Faraday's law, is 90° behind the sinusoidal electromotive force; accordingly, the maximum of the induction and hence of the current is 90° behind the electromotive force. It will be noted, however, that the fundamental of the current wave has its maximum in advance of the maximum of the complex wave by an angle ψ, the hysteretic angle of advance, in this case equal to 29° 23′. The fundamental current wave lags then $90° - \psi$ behind the electromotive force and represents power consumed by hysteresis, with a power-factor $\cos(90° - \psi) = \sin\psi$.

If θ, the phase-angle of the harmonic, is between 0° and 180°, we find that the right-hand side of the complex current wave will have a hump, as in Fig. 2. The fundamental will be advanced to the left so as to lag less than 90° behind the electromotive force, representing power taken by hysteresis—a possible case.

If, however, θ is between 180° and 360°; that is, if the harmonic is made to be behind instead of in advance of the fundamental, the hump on the current curve will be found on the left, and the fundamental will be shifted to the right so as to lag more than 90° behind the electromotive force, representing power given out by hysteresis—an impossible case. In this case the hysteresis loop would needs be traversed in the reverse direction from the actual counter-clockwise direction and its area would represent work given out per cycle. Fig. 2 turned upside down would represent such a case.

DERIVATION OF HYSTERESIS LOOP.

A hysteresis loop consists in plotting corresponding values of B and H in rectangular coördinates. A hysteresis loop corresponding to the curves of Fig. 2 is accordingly readily plotted. H is directly proportional to I, and hence the curve for I may be taken as a curve for H. Corresponding values of H and B

are taken directly from the curves in Fig. 2 and plotted in rectangular coördinates to give the hysteresis loop of Fig. 3.

The interpretation is this: we arbitrarily assume a complex current I, made up of a fundamental and third harmonic, Fig. 2. The sinusoidal induction B and electromotive force will then be as shown in Fig. 2. The hysteresis loop which would produce the assumed distortion is shown in Fig. 3.

When $\theta = 0°$, or $180°$, the hysteresis loop becomes a curved line; the ascending and descending curves coincide and enclose no area, representing therefore no hysteresis loss, although the permeability varies. These cases are shown by curves 5 and 13 in Figs, 14 and 15. They are impossible limiting cases; the angle θ must accordingly be more than 0° and less than 180°, and positive.

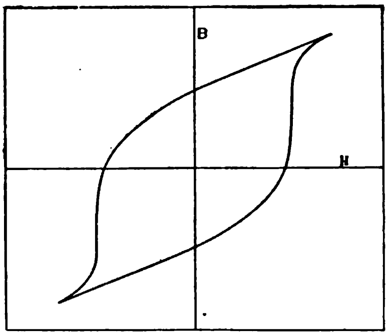

FIG. 3.—Hysteresis loop corresponding to Fig. 2.

It will be shown later that θ must be greater than 30°, and that all the curves in Fig. 14 (corresponding to values of θ from 0° to 30°) are impossible.

The hysteresis loops derived in this paper from consideration of the fundamental and third harmonic only in the current wave, have an unnatural appearance, particularly near the maximum values. Hence it is concluded that the fifth and other higher harmonics are necessary in the complex wave in order to derive therefrom a more normal hysteresis loop, particularly when saturation in the iron is passed.'

LIMITING VALUES OF AMPLITUDE OF HARMONIC, AND OF HYSTERETIC ADVANCE.

It will be found that for $\theta = 0°$ the amplitude β of the harmonic cannot be greater than $\frac{1}{3}$; and for $\theta = 180°$, the value of β cannot be more than $\frac{1}{3}$, the fundamental being taken as unity. The limiting possible values of β for various values of θ are shown in Fig. 4 and are given in Table I. If β exceeded

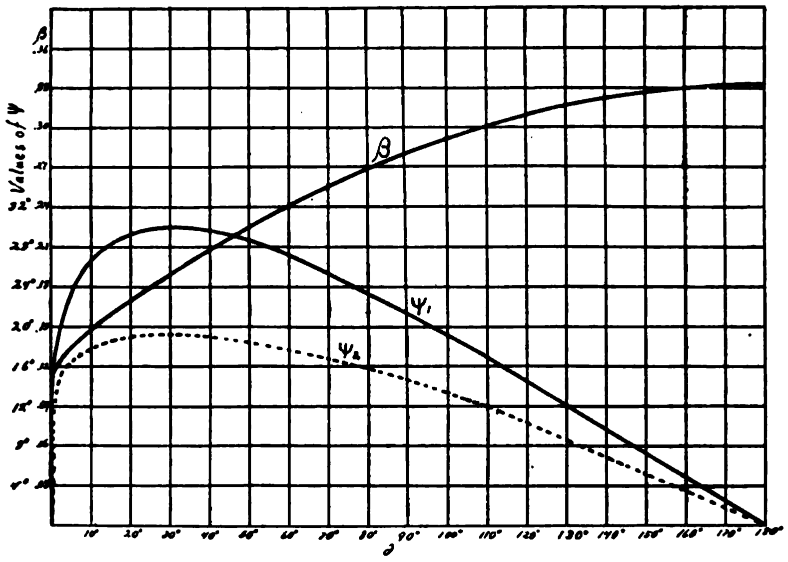

FIG. 4.—Limiting values of β (amplitude of the third harmonic) and ψ (hysteretic advance) for various phase positions of third harmonic.

TABLE I.

LIMITING VALUES OF β AND ψ FOR VARIOUS VALUES OF θ.

θ	β	ψ	θ	β	ψ
0°	0.111	0°	40° 6′	0.211	29° 34′
	0.112	5° 41′	45° 14′	0.220	29° 6′
	0.113	7° 59′	46° 34′	0.222	27° 43′
	0.116	11° 8′	57° 44′	0.240	27° 28′
1° 17′	0.120	16° 20′	60° 42′	0.244	27° 1′
1° 45′	0.122	16° 54′	71° 44′	0.260	25° 8′
4° 48′	0.133	22° 30′	76° 48′	0.267	24° 9′
6° 55′	0.140	24° 28′	87° 47′	0.280	21° 56′
8° 34′	0.144	25° 35′	95° 54′	0.289	20° 12′
12° 52′	0.156	27° 40′	107° 16′	0.300	18° 4′
14° 15′	0.160	28° 15′	120° 40′	0.311	14° 34′
17° 37′	0.167	28° 57′	134° 4′	0.320	11° 22′
22° 44′	0.178	29° 41′	143° 35′	0.322	10° 23′
23° 47′	0.180	29° 47′	157° 18′	0.330	5° 43′
30° 39′	0.192	30° 00′	180°	0.333	0°
33° 59′	0.200	29° 56′			

the limiting value, the resultant current would have two maxima in a half cycle, as in Fig. 17 of the Appendix. This is impossible, as it would mean corresponding maxima in the values of H. This would cause H to have four maxima per cycle, as in Fig. 18, while B has but two.

Curve ψ_1, in Fig. 4, shows the greatest possible values of the angle of hysteretic advance for various values of θ; this curve corresponds to limiting values of β given in curve β. Other values of β will give a smaller value for ψ as shown in curve ψ_2 which shows ψ for $\beta = \frac{1}{8}$ for all values of θ. It is seen that in no case can ψ be greater than 30°.

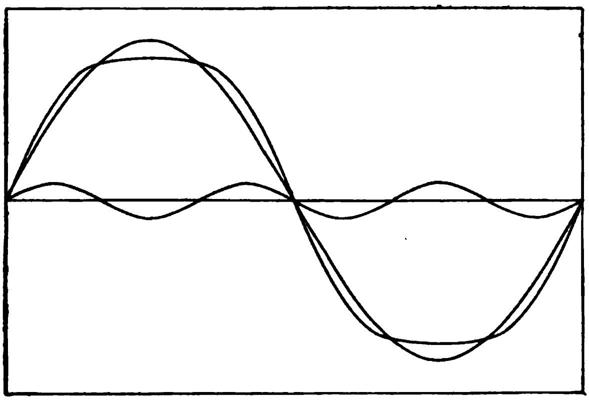

FIG. 5.—Complex current curve, fundamental and third harmonic for $\theta = 0$. See Table II for data for all curves.

For the method for determining the limiting value of β, and also for ψ, as given in the table and shown in Fig. 4, a full discussion of which is given in the appendix, we are indebted to Professor James McMahon.

A year ago Mr. M. C. Carpender, at the suggestion of one of us, plotted a large number of complex current curves and hysteresis loops for different values of θ and β, with a view to determining their limiting values by a method of cut and trial; but it proved impossible in this way to get definite results.

DISCUSSION OF CURVES.

The curves in Figs. 5-13 show the complex current wave resulting from a fundamental and third harmonic in various phase positions from 0 to 180°, the amplitude of the harmonic being in all cases the greatest possible according to values for β shown in Fig. 4. The data referring to these curves are given in Table II.

TABLE II.

Data Relative to Curves in Figs. 5–13.

Curve No.	θ	β	α	ψ	I	I′
5	0°	0.111	0°	0°	1.006	0.8890
6	2°	0.122	16° 54′	17°	1.007	0.8832
7	5°	0.135	22° 48′	23°	1.009	0.8833
8	20°	0.172	29°	29° 30′	1.015	0.9250
9	30°	0.193	29° 33′	30°	1.019	0.9624
10	45°	0.220	28° 38′	29° 22′	1.024	0.9868
11	90°	0.283	19° 36′	20° 30′	1.039	1.1850
12	135°	0.321	10° 12′	10° 45′	1.050	1.2950
13	180°	0.333	0°	0°	1.053	1.3330

θ is the phase relation of the third harmonic to the fundamental at the origin.

β is the ratio of the maximum ordinates of the fundamental and third harmonic (critical value).

ψ is the phase difference between the maxima of the distorted and fundamental curves.

$90 - \psi$ is lag of fundamental component of current behind e.m.f.

$90 - \alpha$ is lag of equivalent sine current behind e.m.f.

I and I' are the maxima of the equivalent sine curve and distorted curve, respectively, the maximum value of the fundamental being unity.

The amount of shifting to the left of the fundamental (the hysteretic advance), is readily observed in each case, this being ψ. The hysteretic angle ψ increases with hysteresis loss, the power-factor for hysteresis being cos ψ. In Figs. 5 and 13, for $\theta = 0°$ and 180°, ψ is 0 and the maxima of the fundamental and complex waves are coincident; hence power consumed by hysteresis is zero.

The corresponding hysteresis loops for all cases are shown in Figs. 14 and 15. Loops 5 and 13, for $\theta = 0°$ and $\theta = 180°$, have no area, which likewise indicates that the power consumed by the hysteresis is zero.

Curves shown in Figs. 5 to 9 are for various values of θ equal to or less than 30°, the corresponding hysteresis loops being shown in Fig. 14. The upward turn of these loops, when θ is less than 30°, shows these cases to be impossible; for they would indicate an increase instead of decrease in the permeability for increasing values of induction beyond saturation. Possible values of θ must accordingly be between 30° and 180°

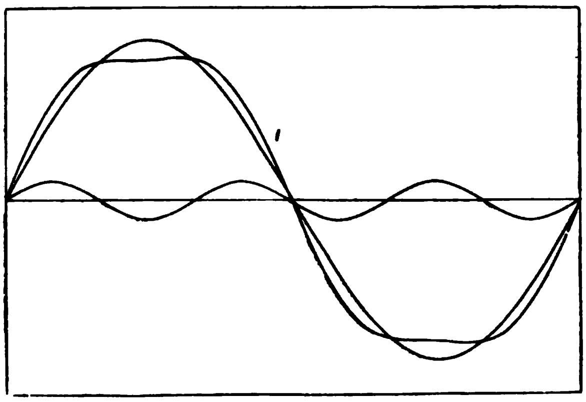

FIG. 6.—Complex current curve fundamental and third harmonic for $\theta = 2°$.

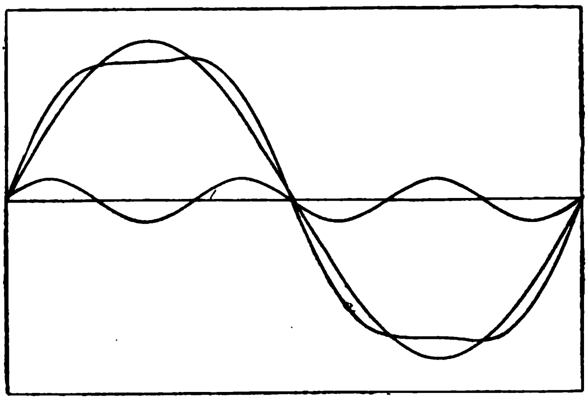

FIG. 7.—Complex current curve, fundamental and third harmonic for $\theta = 5°$.

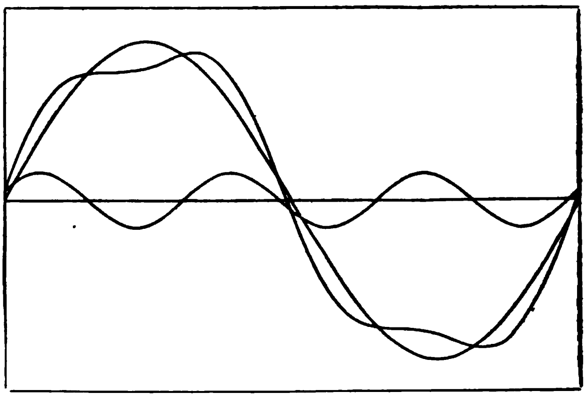

FIG. 8.—Complex current curve, fundamental and third harmonic for $\theta = 20°$.

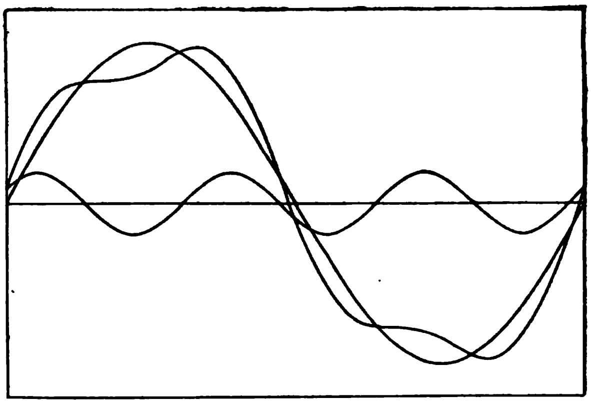

FIG. 9.—Complex current curve, fundamental and third harmonic for $\theta = 30°$.

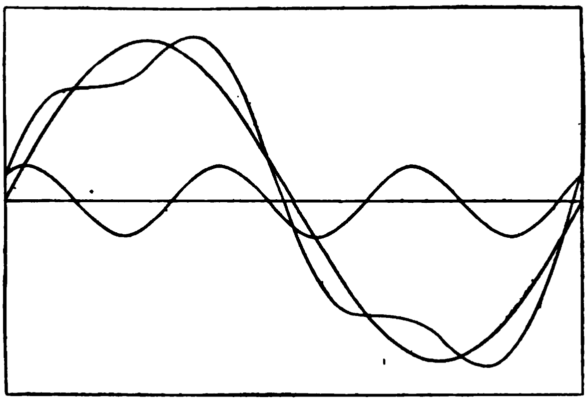

FIG. 10.—Complex current curve, fundamental and third harmonic for $\theta = 45°$.

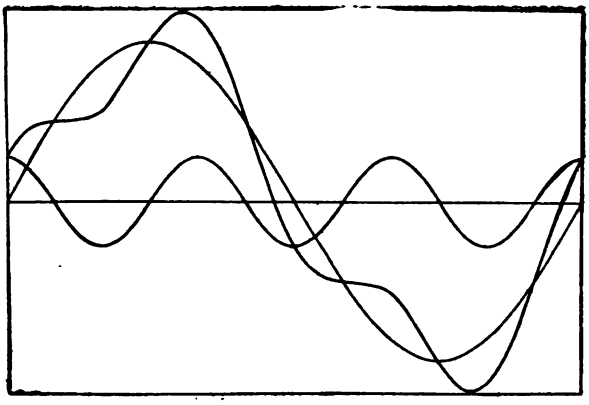

FIG. 11.—Complex current curve, fundamental and third harmonic for $\theta = 90°$.

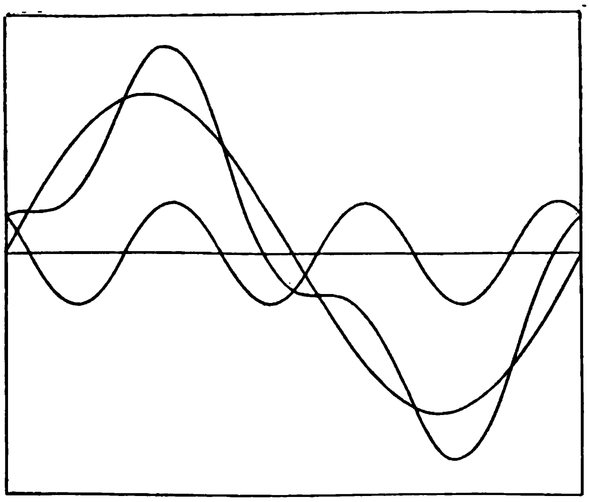

FIG. 12.—Complex current curve, fundamental and third harmonic for $\theta = 135°$.

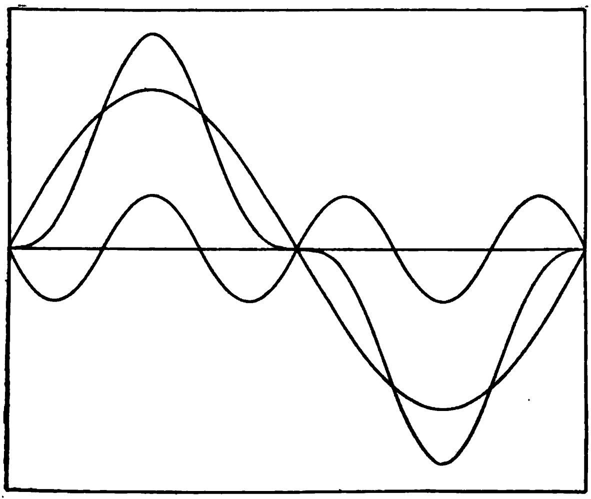

FIG. 13.—Complex current curve, fundamental and third harmonic for $\theta = 180°$.

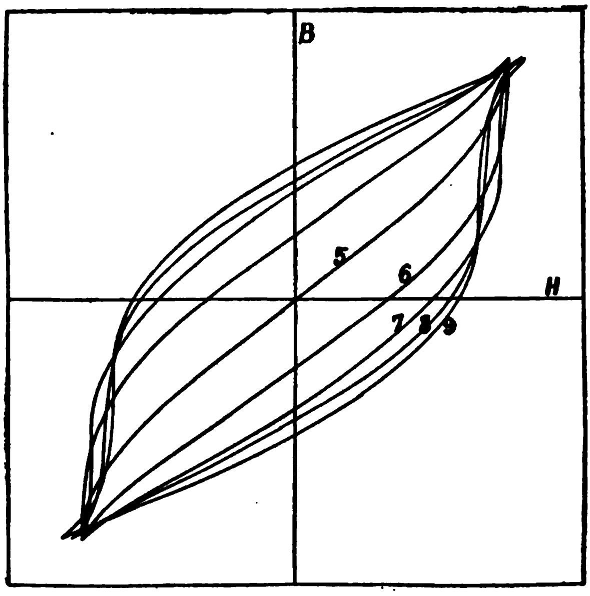

FIG. 14.—Hysteresis loops corresponding to Figs. 5–9. $\theta = 30°$ or less.

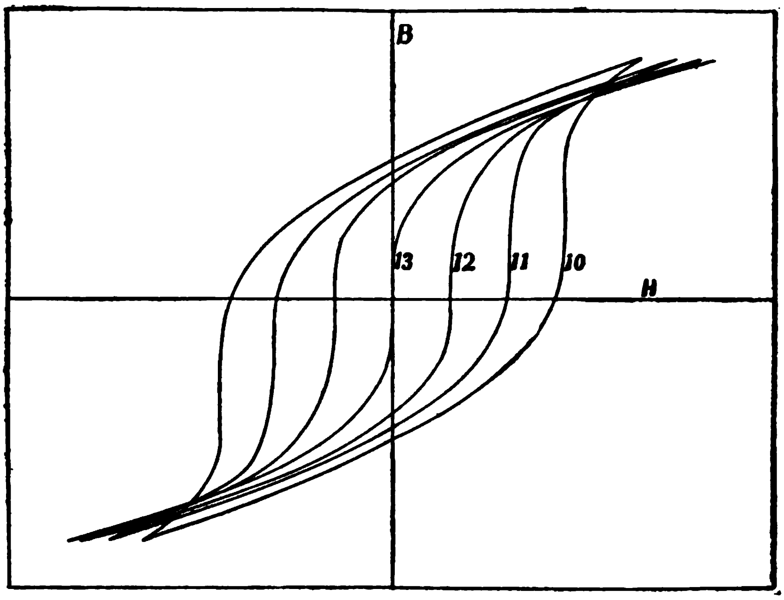

FIG. 15.—Hysteresis loops corresponding to Figs. 10–13. θ greater than 30°

RELATION BETWEEN AREA OF HYSTERESIS LOOP AND ANGLE OF HYSTERETIC ADVANCE.

Since only the fundamental in the current wave represents power, and the harmonics are wattless, we have the same power represented by the fundamental as by the complex wave. Hence if values of H be taken from the fundamental current curve, and a hysteresis loop plotted, it will have the same area as though H were taken from the complex wave, as was done in deriving the loops in Figs. 14 and 15. In this case, however, with H as well as B sinusoidal, the hysteresis loop would form an ellipse, the area of which can be shown* to be

$$A = \pi\ XY \sin \psi.$$

Here X and Y represent the maximum values of the sinusoidal magnetizing force H and induction B, respectively.

As has just been shown, the area of this ellipse can likewise be taken as the area of the loop when the complex wave of current is taken. It at once follows that

$$\sin \psi = \frac{A}{\pi\ X\ Y} = \frac{1}{\pi} \cdot \frac{A}{X'Y} \cdot \frac{X'}{X} = \frac{1}{\pi} \cdot \frac{A}{X'\ Y} \cdot \frac{I'}{F}.$$

Here F is the maximum value of the fundamental and I' the maximum value of the complex current wave; X and X' being corresponding values of magnetizing force. $X'\ Y$ is the area of the rectangle enclosing the hysteresis loop.

For $\frac{A}{X'Y,}$ write ρ; and for $\frac{I'}{F}$ write f.

For any hysteresis loop the value of the hysteretic advance may then be derived from the following expression:

$$\text{Sin } \psi = \rho\, f/\pi,$$

---

* Let the induction and magnetizing force be respectively $y = Y \sin \omega t$ and $x = X \sin (\omega t - \psi)$. Plotted in rectangular coördinates, the resulting figure will be an ellipse. Its area (see translation of Goursat's Mathematical Analysis, p. 185) will be

$$A = \tfrac{1}{2} \int_0^{2\pi} (x\, d\, y - y\, d\, x).$$

$$= \tfrac{1}{2} \int_0^{2\pi} X\ Y\ \{\sin \omega t \cos (\omega t - \psi) - \sin (\omega t - \psi) \cos \omega t\} \omega\, d\, t$$

$$= \frac{X\ Y}{2} \int_0^{2\pi} (\sin^2 \omega t \sin \psi + \sin \psi \cos^2 \omega t)\ \omega\, d\, t$$

$$= \pi\ X\ Y \sin \psi.$$

where ρ is the ratio of the area of the hysteresis loop to the enclosing rectangle, and f is a form-factor—the ratio of the maximum values of the complex and fundamental current waves. If the result depended upon ρ only, hysteretic advance could be readily and directly determined from area of the hysteresis loop. The results are modified, however, by the presence of f, which is unsatisfactory, for it makes the direct determination in this way impossible. Table II gives values of I' for curves 5–13.

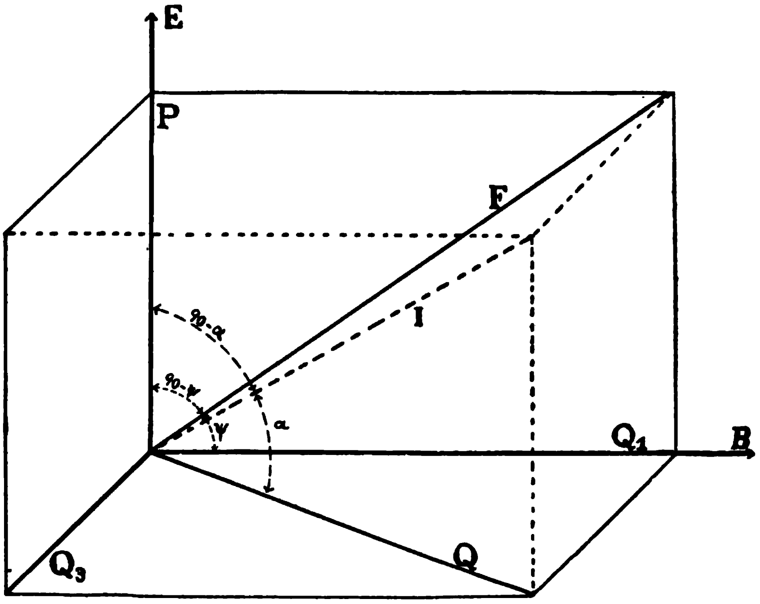

FIG. 16.—Vector representations in three dimenions of a complex current. E is sine electromotive force; F is fundamental current; Q_3, harmonics; and I is the equivalent sine current.

VECTOR REPRESENTATION OF COMPLEX CURRENT.

Without iron, where current as well as electromotive force is sinusoidal, as shown in Fig. 1, the vector representation of these quantities as lines in a plane is well known.

Let us take, however, such a case as shown in Fig. 2, in which the electromotive force E is sinusoidal and the current I, on account of iron, is complex, being composed of a fundamental F and third harmonic Q_3.

Considering first the fundamental F, this may be considered as composed of two components, Fig. 16, a power component

P in phase with E, and a quadrature or wattless component Q_1 at right angles to E; that is, $F = \sqrt{P^2+Q_1^2}$. These quantities E, F, P, and Q_1 are all sine functions of the same frequency and are graphically represented in one plane. The induction B is in the direction of Q_1, and is also a sine function of fundamental frequency. The fundamental F lags behind E by an angle $90-\psi$ (as in Fig. 2); ψ is the angle between Q_1 (or B) and F. In Fig. 16 and its discussion all quantities represent virtual or square root of mean square values.

The harmonic Q_3 has no power component in phase with E; it is entirely wattless, as has been shown, and hence is to be represented graphically in quadrature to E. But it may be shown* that $I = \sqrt{F^2+Q_3^2}$, which corresponds to a graphical construction in which Q_3 and F are two sides of a rectangle and I the diagonal. As Q_3 is thus at right angles to both E and F, it is drawn in the third dimension at right angles to the plane of fundamental frequency in which lie E, F, P, and Q_1.

The total current is I, the diagonal of the rectangular parallelopiped. I is the equivalent sine wave representing the complex current. In phase it is as represented in Fig. 16, lagging behind E by an angle $90-\alpha$. In magnitude it is such as to have the same square root of mean square value as the complex wave. We have seen that

$$I = \sqrt{F^2+Q_3^2};$$

We also have

$$I = \sqrt{P^2+Q_1^2+Q_3^2}.$$

In the usual treatment confined to one plane, the plane taken is the diagonal one in which lie E and I. The equivalent sine current I may be resolved into a power component P of fundamental frequency in phase with E, and an equivalent wattless component Q at right angles to E. The component Q is itself complex, consisting of two components each wattless; namely, Q_1 of fundamental frequency and the harmonic Q_3. We have

then $$Q = \sqrt{Q_1^2+Q_3^2},$$
and $$I = \sqrt{P^2+Q^2}.$$

Power is the product of E and P. Considering the fundamental sine curve, we have for power in terms of F:

$$W = E F \cos (90-\psi).$$

---

*This is independent of the phase position θ of the harmonic. See F. Bedell, "The Principles of the Tranformer," p. 391.

If we consider the equivalent sine curve, we have for power in terms of I:

$$W = E\,I \cos\,(90 - \alpha).$$

Each is correct, the two expressions being practically identical. An error (numerically small) would be made by confusing the fundamental and equivalent sine curves, and interchanging the values of F and I, or of ψ and α. It is seen that

$$\frac{\sin \alpha}{\sin \psi} = \frac{F}{I} = \frac{F}{\sqrt{F^2 + Q^2_3}}$$

For the curves in Figs. 5–13, the values for α and ψ are given in Table II; also I, the maximum value of the equivalent sine wave. In constructing the curves, F has been taken as unity; then $Q_3 = \beta$ (see table).

The graphical construction of Fig. 16 will include the representation of higher harmonics if we include them all in Q_3; that is, in place of Q_3 we should have $Q_x = \sqrt{Q_3^2 + Q_5^2 \ldots Q_n^2}$. Separately and collectively the harmonics are wattless, and are at right angles to both E and F. Their separate representation in three dimensions is not possible; for, in addition to being at right angles to E and F, each one should be at right angles to each other one, requiring an additional dimension for each harmonic above the third. This representation is, however, unnecessary, for, since all are wattless, their collective representation as one line, Q_3, meets all requirements.

If we are to represent all quantities in one plane only, the vector representation is correct for each frequency, and for the equivalent sine curve separately; components of different frequencies so drawn are not to be combined vectorially, but are to be added by taking the square root of the sum of the separate squares.

CONCLUSION.

We conclude that an alternating current is distorted when iron is present by the introduction of a third harmonic in advance of the fundamental by an angle θ which is greater than 30° and less than 180°.

Taking the fundamental as unity, this harmonic cannot exceed a definite value (see Table I) of about 0.192 for $\theta = 30°$, and 0.333 for $\theta = 180°$.

The angle ψ of hysteretic advance due to the third harmonic cannot exceed 30°.

From the shape of the hysteresis loop obtained from the third harmonic only, it is concluded that iron introduces higher harmonics in addition to the third.

Three dimensions, as Fig. 16, are required for the vectr representation of the complex current wave.

APPENDIX.*

RELATION BETWEEN θ AND β.

We wish to find the condition which holds at the transition state, Fig. 19, separating the impossible case of two maxima and one minimum, Fig. 17, and the possible case of one maximum and no minimum, Fig. 20. The form of hysteresis loop, Fig. 18, corresponding to Fig. 17, shows the impossibility of the former case.

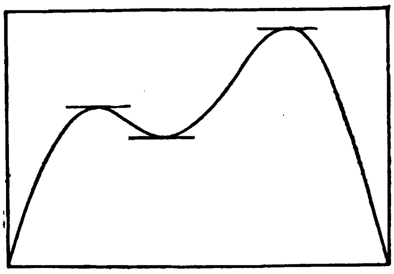

FIG. 17.—Two crests, one trough, and two inflexions.

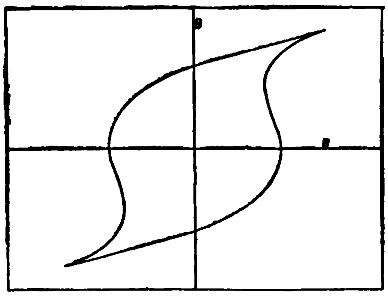

FIG. 18.—Hysteresis loop corresponding to Fig. 17, with four maxima for H which would result were the limits of β given in Fig. 4 exceeded.

We proceed to find the condition imposed upon θ and β so that the graph of

$$f(t) = \sin \omega t + \beta \sin (3 \omega t + \theta)$$

shall have no trough or minimum in the first half cycle.

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* Due to Professor James McMahon.

By differentiation we have

$$f'(t) = \omega [\cos \omega t + 3\beta \cos(3\omega t + \theta)] = 0,$$

hence the positions of the crests and troughs are given by the equation

$$\cos \omega t + 3\beta \cos(3\omega t + \theta) = 0.$$

We shall find the condition that this equation may have two roots equal; and, subject to this condition, we shall find the next root; this will give the position of the only proper crest or maximum in the first half-cycle.

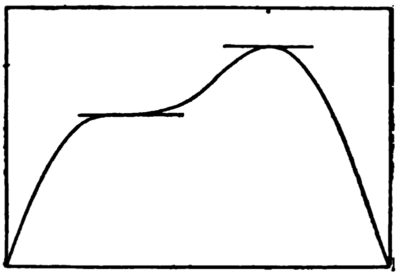

FIG. 19.—One crest and one (horizontal) inflexion.

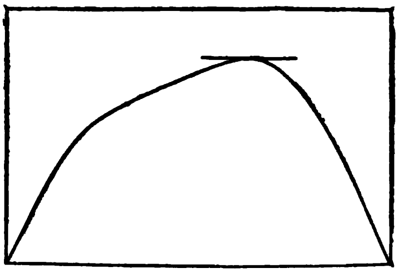

FIG. 20.—One crest and one (oblique) inflexion.

For convenience let $9\beta = 1/a$ and write x for ωt.

Then

$$\cos(3x + \theta) + 3a \cos x = 0.$$

That is

$$\cos 3x \cos \theta - \sin 3x \sin \theta + 3a \cos x = 0.$$

Therefore

$$(4\cos^3 x - 3\cos x)\cos\theta - (3\sin x - 4\sin^3 x)\sin\theta + 3a\cos x = 0.$$

Dividing through by $\cos^3 x$ we have

$$(4 - 3\sec^2 x)\cos\theta - (3\tan x \sec^2 x - 4\tan^3 x)\sin\theta + 3a\sec^2 x = 0$$

Replacing $\sec^2 x$ by $1+\tan^2 x$, we get the following cubic for $\tan x$:

$$\sin\theta\tan^3 x+3\,(a-\cos\theta)\tan^2 x-3\sin\theta\tan x+(3\,a+\cos\theta)=0.$$

Now it is known in the theory of equations that the cubic

$$a\,x^3+3\,b\,x^2+3\,c\,x+d=0 \tag{1}$$

has two equal roots when

$$4\,(a\,c-b^2)\,(b\,d-c^2)=(a\,d-b\,c)^2,$$

the equal roots being given by

$$x_1=x_2=\frac{b\,c-a\,d}{2\,(a\,c-b^2)}$$

and the third root by

$$x_3=-\frac{3\,b}{a}-\frac{b\,c-a\,d}{a\,c-b^2}.$$

For our cubic the condition for equal roots becomes

$$-4\,(a^2-2\,a\cos\theta+1)\,(3\,a^2-2\,a\cos\theta-1)=(4\,a\sin\theta)^2,$$

whence

$$\cos\theta=\frac{3\,a^4+6\,a^2-1}{8\,a^3}; \tag{2}$$

and the expressions for the roots become

$$\tan x_1=\tan x_2=\frac{2\,a\sin\theta}{a^2-2\,a\cos\theta+1}, \tag{3}$$

$$\tan x_3=\frac{-3\,(a-\cos\theta)}{\sin\theta}-\frac{4\,a\sin\theta}{a^2-2\,a\cos\theta+1}. \tag{4}$$

With the aid of (2), the last expression reduces to

$$\tan x_3=-\frac{(1-a^2)\,(1+3\,a^2)}{8\,a^3\sin\theta}.$$

It is convenient to let $\frac{1}{a}=b$, then $b=9\,\beta$, and

$$\tan x_3=-\frac{(b^2-1)\,(b^2+3)}{8\,b\sin\theta}, \tag{5}$$

wherein θ is given by (2), or by

$$\cos\theta=\frac{3+6\,b^2-b^4}{8\,b}, \tag{6}$$

or (in a form better adapted to logarithmic computation) by

$$\sin\theta=\frac{(b^2-1)^{\frac{3}{2}}\,(9-b^2)^{\frac{1}{2}}}{8\,b}. \tag{7}$$

This equation, wherein $b = 9\beta$, gives the desired relation between θ and β. If we assume a given value of θ and solve for β, the value so obtained would be the greatest value of β that could be used with the given value of θ without obtaining a trough as in Fig. 17, which corresponds to the impossible hysteresis loop of Fig. 18.

To determine ψ, the phase displacement of the crest, we proceed as follows:

Eliminating $\sin\theta$ from (5) by means of (7) we obtain

$$\tan x_3 = -\frac{b^2+3}{\sqrt{(b^2-1)(9-b^2)}}. \qquad (8)$$

Hence the position of the crest is given by

$$\omega t = \pi - \tan^{-1}\frac{b^2+3}{\sqrt{(b^2-1)(9-b^2)}}. \qquad (9)$$

Now the crest of the fundamental curve ($y = \sin\omega t$) is given by $\omega t_1 = \frac{\pi}{2}$. Hence the displacement of the crest due to the presence of the third harmonic is given by

$$\psi = \omega(t - t_1) = \frac{\pi}{2} - \tan^{-1}\frac{b^2+3}{\sqrt{(b^2-1)(9-b^2)}}, \qquad (10)$$

wherein $b = 9\beta$. This gives ψ in terms of β, when θ is determined as in (7).

Since neither (7) nor (10) is readily solvable for b, it is best to assign values to b and compute corresponding values for θ and ψ. Equation (7) shows that b cannot be less than 1 nor greater than 3; and equation (6) shows that $b = 1$ corresponds to $\theta = 0$, and $b = 3$ to $\theta = \pi$. Table I gives values of θ and ψ computed from (7) and (10), by letting b run from 1 to 3 at convenient intervals, not always equi-distant. The corresponding values of β run from 0.111 to 0.333.

Cornell University, June, 1906.

DISCUSSION ON "THE EFFECT OF IRON IN DISTORTING ALTERNATING-CURRENT WAVE-FORM" AT NEW YORK, SEPTEMBER 28, 1906.

Charles Proteus Steinmetz: This paper deals with the wave-shape distortion produced in alternating-current circuits by the introduction of iron. It is a theoretical paper, and while of scientific interest appears at first of rather little practical value to the electrical engineer. There is, however, to-day only a very short step between pure scientific investigation and engineering practice; and I hope to show you that the phenomena dealt with in this paper, and similar phenomena, are of very great practical importance in alternating-current distribution; that is, wave-shape distortion may lead to effects not only very marked and pronounced but occasionally disastrous. In general, in investigating the effect of iron in alternating-current circuits, the curve of exciting current is calculated from the hysteresis cycle of the iron. Dr. Bedell proceeds inversely by superposing different harmonics of current. From these complex currents he produces a hysteresis loop, noting whether this hysteresis loop is a reasonable one or not, and deriving therefrom relations regarding the relative intensity and phase of the triple harmonic in the wave of exciting current. As far as the investigation goes, it extends only to the fundamental and triple harmonics; the investigation of higher harmonics is left to a future occasion.

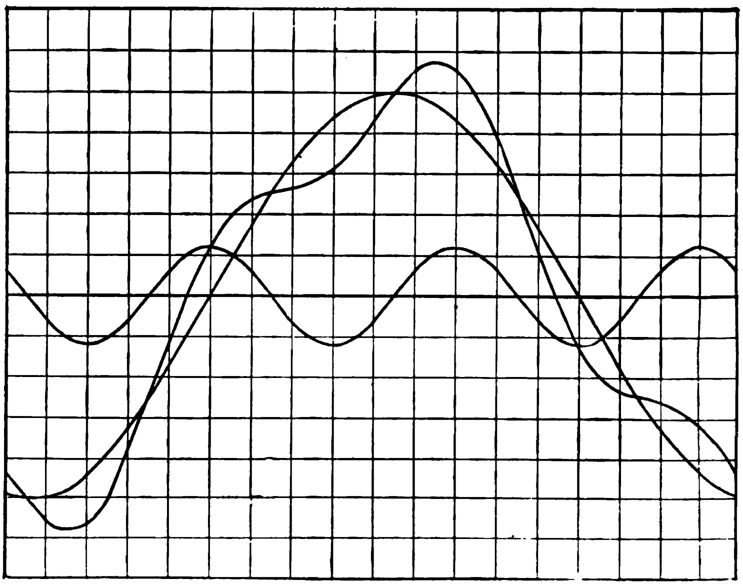

FIG 1

These higher harmonics obviously modify to a certain extent the conclusions arrived at by assuming merely the fundamental and triple harmonic as present. For instance, by superposing a triple harmonic upon the fundamental wave, one gets a wave of the shape shown in Fig. 1., with a hump on the rising side and a hollow on the decreasing side. Introducing a triple harmonic of higher amplitude causes the hump to develop into a double peak as in Fig. 2. It is obvious that a double peak cannot exist, because whatever relation may exist between the magnetism and the magnetizing current, the current must rise as long as the magnetism rises; and therefore the maximum possible value of the triple harmonic is that value which does not yet give a downward bend, but merely flattens the current wave on the rising side. This maximum amplitude of the third harmonic can, however, be exceeded if higher harmonics are present. Assume for instance a fifth harmonic which has such a phase relation as to be negative at *A* Fig. 2, and positive at *B*, and then superpose this fifth harmonic on the double-peaked wave; it will be seen that it cuts off the peak and fills up the hollow, and gives a wave which represents a possible hysteresis cycle, as seen in Fig. 3. The effect of the fifth harmonic, then, is to permit the existence of a triple harmonic, larger than could exist in the absence of the fifth harmonic. It is quite probable that not infrequently in the exciting current there occur triple-harmonic currents higher than the maximum value cal-

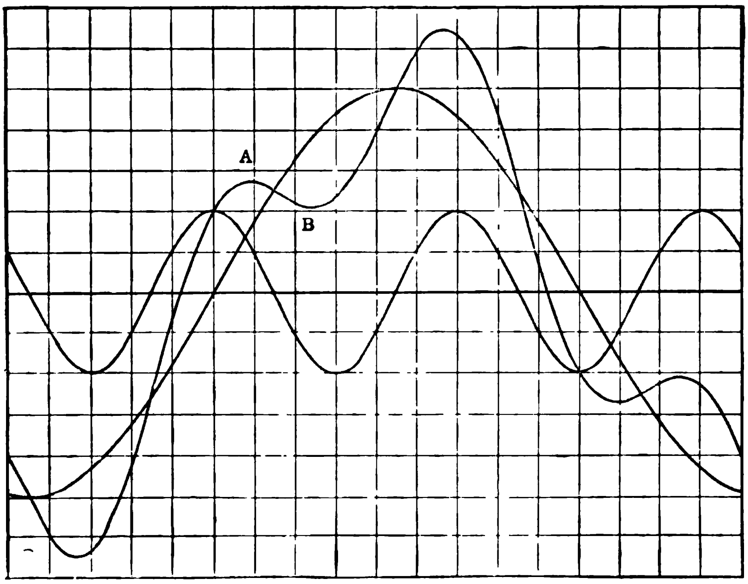

FIG 2

culated in Dr. Bedell's paper, and the double peak is cut off by the fifth harmonic. The fifth harmonic being in phase, approximately, at the maximum value of magnetism, is approximately in opposition at the zero of magnetism, where the double peak tends to form. This brings up the question of the desirability of extending Dr. Bedell's investigation to still higher harmonics, the fifth, seventh, ninth, etc.

An interesting investigation of the wave-shape distortion of the exciting current is given in a paper presented to the Institute May 1896 by C. K. Huguet. It was this: let there be a sine wave of electromotive force, producing a sine wave of magnetism, and from the hysteresis cycle construct the wave of exciting current. This exciting current can be resolved into two components: one component symmetrical with regard to the wave of magnetism, or wattless current; the other symmetrical with regard to the wave of electromotive force, representing power. The component in phase with the magnetism will be found to be greatly distorted, while the component in phase with the electromotive force is practically a sine wave, as shown in Fig. 4. I have checked this in quite a number of cases and it agrees nicely, except that there always are some small very high harmonics in the energy wave which makes this curve horizontal at the

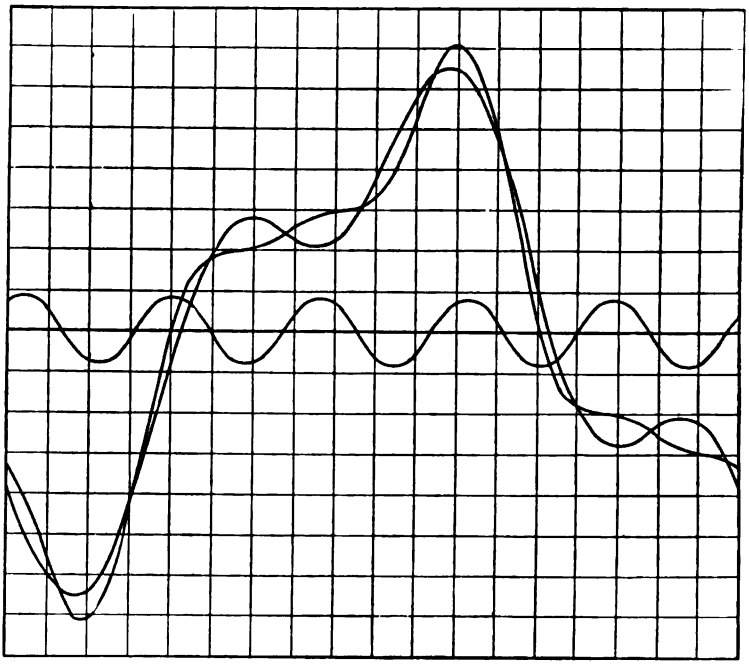

Fig 3

zero value. That is, the harmonics symmetrical with regard to the electromotive force are noticeable only at the zero point, as a flattening out. The magnetism curve at this point is horizontal, so that the resultant current curve must be horizontal also. This could be expressed by stating that the distortion of the wave of the exciting current is due, not to the energy lost in the iron, but to the magnetic characteristic or the bending of the saturation curve, and therefore it is this curve which we should endeavor to construct, the magnetic characteristic as it would be given by a magnetic cycle, in the absence of hysteresis loss. This would probably give approximately the higher harmonics in the exciting curve wave.

Sometime in 1881 or 1882 Dr. Froehlich noticed that the magnetic characteristic of the dynamo machine could be approximately represented by a parabolic curve. Dr. Kennelly showed, in 1891*, that the B H curve, or magnetic characteristic of iron, for the higher values, could be expressed by a parabolic curve, an equation of the second degree. Using this equation of a parabola for the relation between B and H, there could be found a strictly mathematical curve, about like B_0 in Fig. 5, which combined with a sine wave representing the hysteresis loss, would fairly closely represent the distorted wave of exciting current.

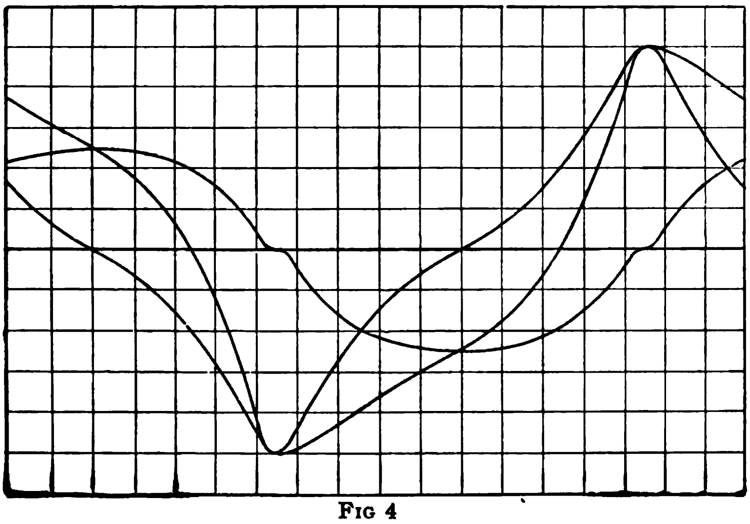
FIG 4

In dealing with hysteresis we have to keep in mind the difference between magnetic hysteresis and the energy lost in the iron. If iron is exposed to an alternating magnetic field, the loss of energy that takes place in the iron, by some form of magnetic

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*Magnetic Reluctance, by A. E. Kennelly, TRANSACTIONS A. I. E. E. Vol. 8, page 485.

friction, is usually expressed as "molecular magnetic friction." This loss seems to be constant, independent of the frequency or wave-shape, depending only on the maximum values of the magnetic induction. If the alternating electrical circuit is the only source of power, and no power is consumed outside of the iron, then the power consumed by molecular magnetic friction must be supplied by the alternating circuit, and is supplied in the form of a hysteresis cycle. In this case molecular magnetic friction and magnetic hysteresis coincide, or rather the magnetic hysteresis measures the molecular magnetic friction. As soon, however, as there is another source of power present, or power can be consumed elsewhere, this coincidence disappears and there is no inherent relation between molecular magnetic friction and magnetic hysteresis. This was shown first by the experiments of Gerosa and Finzi 1891, recorded by Ewing in his work on magnetism. If an alternating current is sent through the magnetic circuit parallel to the lines of magnetic force, at a frequency which is high compared with the frequency of the magnetic cycle, then the hysteresis loop more or less completely collapses; but the molecular magnetic friction still remains, only that now the longitudinal alternating current supplies all or nearly all the power. The reverse is the case where there are loose laminations in a transformer. It will be found that the hysteresis loop is extended and the electric circuit in the form of a hysteresis loop supplying more power than is consumed in the iron by molecular magnetic friction; the difference is consumed in the vibration of the laminations, resulting in noise. Where energy is supplied from an outside source, it may go so far as not only to make the hysteresis loop disappear, but to make it

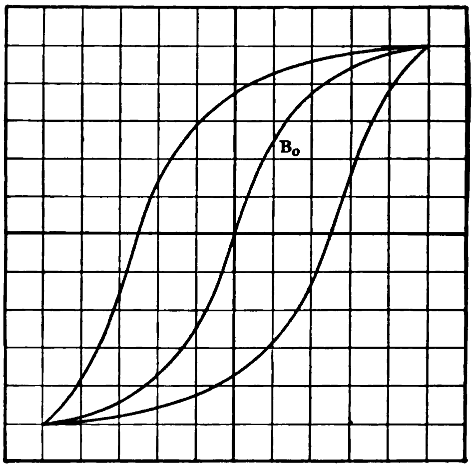
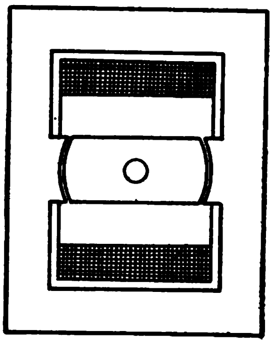


FIG. 5.

negative. Some interesting conditions where the hysteresis loop could be flattened out or turned over were investigated by Mr. Eickemeyer and myself in 1891, on a magnetic circuit of the shape of that of a shell-type transformer, shown in Fig. 6, in which the central core could be rotated. We found that such an arrangement when running at synchronism would give all kinds of hysteresis loops; for instance; that the more the apparatus as motor was loaded the fatter became the hysteresis loop. Whenever the friction is supplied by an outside source the hysteresis loop collapses, and reverses by driving the rotor by power. Some hysteresis loops of this apparatus are given in my second paper on the Law of Hysteresis.*

These overturned magnetic cycles differed considerably from the typical hysteresis cycle, Fig. 5. A typical hysteresis cycle, however, can be made to contract, disappear, and reverse in the following manner:



Diagrammatic View of Eickemeyer Humming Bird

FIG. 6.

Two equal exciting coils A and B, in Fig. 7, at right angles with each other in space, are energized by two equal sinusoidal quarter phase e.m.f's. so giving a uniformly rotating magnetic field. In the center of this field is a movable iron disc, C. With this disc at standstill, the line of resultant magnetism in the disc $Y_1 Y_1^1$, lags behind the line of resultant rotating m.m.f. XX^1 of the exciting coils, by the angle of hysteretic lead α, and the relation of impressed e.m.f. and so of magnetic flux, and of exciting current in the coils A and B gives the typical hysteresis cycle, Curve I, Fig. 8.

With the disc C rotating below synchronism, the angle $X O Y = \alpha$ remains the same, the hysteresis cycle, and thereby the power consumed in the exciting coils, is the same; but the molecular

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*TRANSACTIONS, A. I. E. E., 1892, vol. 9, p. 3.

magnetic friction in the disc, while the same per cycle, decreases with increasing speed, proportional to the decreasing frequency of slip. The difference in the power consumed by hysteresis in the exciting coils, and the power consumed by molecular magnetic friction in the disc, is converted into mechanical work, and such an apparatus, which I called "hysteresis motor," so gives constant torque at all speeds, up to synchronism. If this torque is more than the friction torque, the disc accelerates up to synchronism. At synchronism, molecular magnetic friction disappears, and the line of resultant magnetic flux retains a constant position with regard to the iron, and all the power given by the exciting currents in the form of the hysteresis loop is converted into mechanical power. If this is more than the power consumed by mechanical friction, the line of magnetization runs ahead by the acceleration of the disc, to $Y_2\ Y_2^1$, the angle of hysteretic advance $X\ O\ Y$ decreases, and the hysteresis cycle of

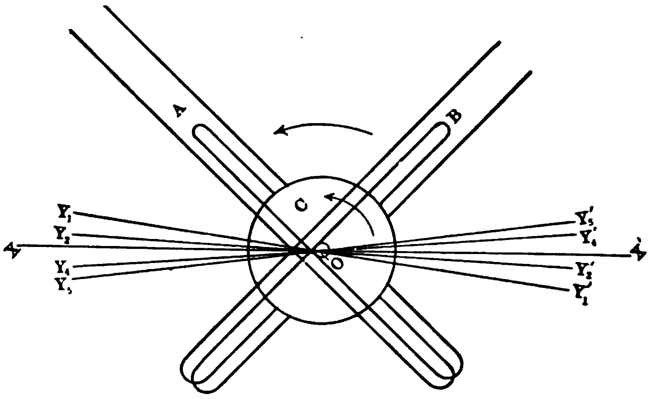

FIG. 7.

the exciting coils so contracts, to Curve II, Fig. 8, giving an area corresponding to the friction torque only. If now the friction torque is supplied by a mechanical driving force, and the disc C not called upon to do any mechanical work, it runs ahead until its line of magnetization $Y\ Y^1$ coincides with the line of resultant m.m.f. $X\ X^1$; that is, the hysteresis angle α disappears, and the curve of magnetism is symmetrical with the curve of exciting current, or the hysteresis loop collapses to Curve III, Fig. 8.

Still greater driving force impressed upon the disc C, sends the line of resultant magnetization ahead of $X\ X^1$, to $Y_4\ Y_4^1$, the angle of hysteretic advance α becomes negative, and the hysteresis loop opens up again, to Curve IV, Fig. 5, but is traversed now in opposite direction, or overturned, representing production of electric power. In this case, the curve of exciting current in A or B has the reverse shape; a hollow on the rising, a hump on the decreasing side.

With increasing driving power, the overturned hysteresis loop IV fattens, until it reaches the same shape as I, but traversed oppositely, and then synchronism is broken, and disc *C* speeds up. Above synchronism, the hysteresis cycle has the normal shape I, but is overturned, the angle of hysteretic advance of phase has reversed its sign, and molecular magnetic friction again consumes power in the disc; but this power is now given by the mechanical driving power, and not by the electric circuit.

Below synchronism, a constant amount of electric power is consumed; above synchronism, a constant amount of electric power is generated in the exciting coils, irrespective of the speed, while the power consumed by molecular magnetic friction in the disc varies proportional to the slip from synchronism, but is the same above as below synchronism.

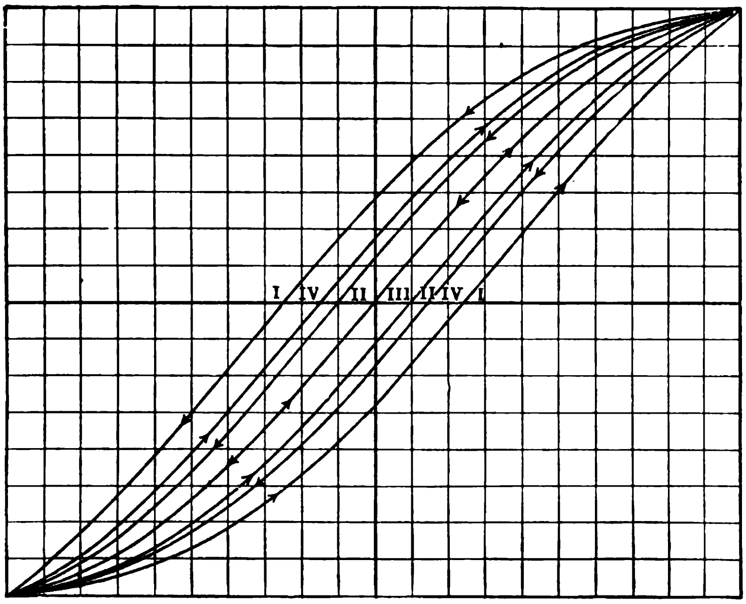

FIG. 8.

The bearing of these wave-shape phenomena on practical engineering will now be considered.

If there be a sine wave of impressed electromotive force, *E*, Fig. 9, or rather of counter electromotive force, it produces a sine wave of magnetic flux *B*. This sine wave of magnetic flux causes an exciting current to flow which is distorted by hysteresis, or rather, as we may say, by the magnetic characteristic, and is given by Curve I. If, however, the transformer is traversed by a sine wave of exciting current, *I* in Fig. 10, we get by the hysteresis loop a wave of magnetism, which is not a sine wave, but which is hollow on the rising side, rises very rapidly and decreases very slowly, at first, and then very rapidly. That is, the wave of magnetism has a pronounced flat top, and the wave of e.m.f. induced thereby is very low for a considerable part of the period, then rises very sharply to a high triangular peak, and falls off just as rapidly, as shown by E in Fig. 10. This peak rises to nearly twice the maximum value of the fundamental sine wave, E_1 Fig. 10. That is, with a sine wave of current traversing an ironclad magnetic circuit, the e.m.f. wave is greatly distorted, and the magnetic circuit generates higher harmonics of e.m.f. mainly of triple frequency.*

Very interesting phenomena result from this wave-shape distortion by the magnetic cycle, if transformers are grouped in such a manner that certain harmonics can not develop.

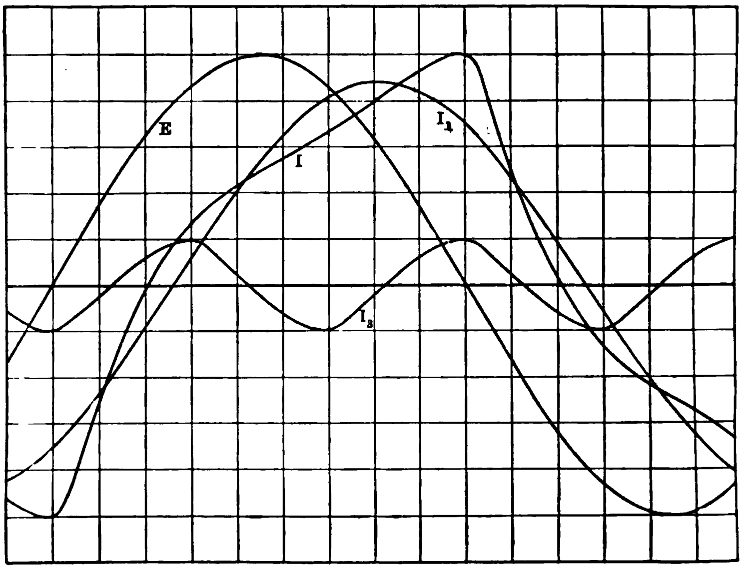

FIG. 9.

In a three-phase system with three transformers connected in delta or ring connection, and a sine wave of impressed e.m.f., the exciting current in the transformers has the usual shape, I in Fig. 9, containing a pronounced third harmonic, which is shown separately as I_3 in Fig. 9, together with all its higher harmonics or

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*For instance with the hysteresis cycle Fig. 5, and a current $I = 10 \sin(\phi + 30)$, the e.m.f. is approximated by the equation: $E = 11.67 \cos(\phi + 2.5°) + 6.64 \cos(3\phi - 3.4°) + 3.24 \cos(5\phi - 11.9°) + 1.8 \cos(7\phi - 10.7°) + 1.16 \cos(9\phi - 4.5°) + 0.80 \cos(11\phi - 22°) + 0.53 \cos(13\phi - 26°) + 0.19 \cos(15\phi - 15°) + \ldots$

"overtunes." The current in the three-phase lines can not contain any third harmonic: the current in line 1 is the resultant of the currents flowing from line 1 to 2, and from 1 to 3, and since these two currents are 60 degrees apart in phase, their third harmonics are 180 degrees apart, or in opposition, hence cancel. That is, the triple-harmonic component of the exciting current circulates in a local circuit through the transformer triangle, without reaching the three-phase lines. All the other harmonics of exciting current appear in the line current.

If the primary coils of the transformers are connected in *Y* or star connection, the secondaries in delta, the primary exciting current does not contain any third harmonic, but the triple harmonic of excitation circulates in the secondary transformer triangle in local circuit.

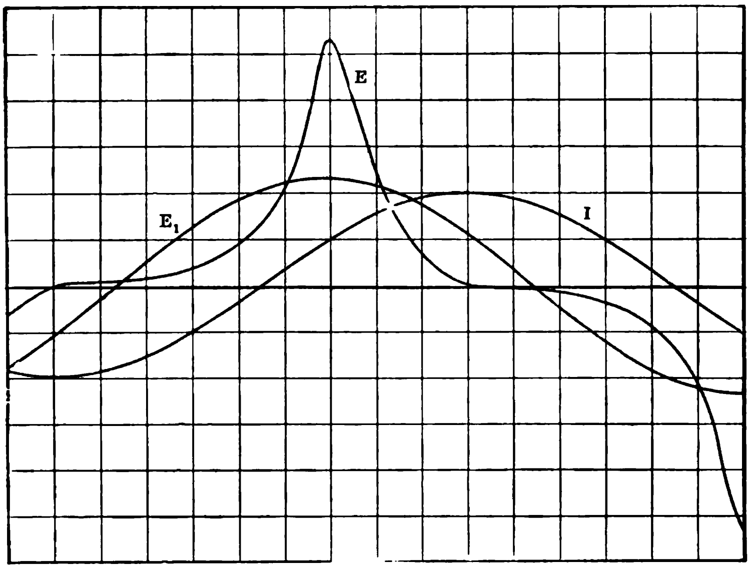

FIG. 10

Perhaps still more interesting is the case of three transformers, connected with their primaries and secondaries in *Y* or star connection in a three-phase system with sinusoidal e.m.f. impressed upon the lines.

In a three-phase system, the three e.m.f's. from the lines to the neutral are 120 degrees apart and so are the three currents. With a sine wave of impressed e.m.f., if the e.m.f's. between lines and neutral were sine waves also, the three exciting currents would contain strong third harmonics. Since these currents are 120 degrees apart, their third harmonics would be $3 \times 120 = 360$ degrees apart, or in phase; that is, all three flow simultaneously toward the neutral. If now the neutral is isolated these triple-frequency components of exciting current have no circuit; that is, cannot flow, and the e.m.f's. between lines and neutral therefore can not be sine waves, but must be distorted by the suppression of the triple-frequency component of exciting currents. This distortion of e.m.f. wave can be due only to a third harmonic and its overtunes, which cancel by combining two such e.m.f's. between line and neutral, under 60 degrees to the impressed e.m.f. while all the other harmonics would not cancel, but appear in the impressed e.m.f. which was assumed as a sine wave.

It follows herefrom, that with a sine wave of three-phase e.m.f. impressed upon a system of Y-connected transformers with isolated neutral, the e.m.f's. between lines and neutral, or potential differences at the transformer terminals, cannot be sine waves, but contain a pronounced third harmonic and its overtunes, but no other harmonics; while the exciting currents contain no third harmonic or multiple thereof, but all other harmonics.

For the hysteresis cycle, Fig. 5, and a sine wave of impressed e.m.f., Fig. 11, shows the wave of exciting current I, the transformer e.m.f. or voltage between line and neutral, E, its fundamental sine wave, E_1, and the sum of all its harmonics, E_3. As seen, the e.m.f., E, is peaked, while the wave of magnetism (not shown) has a flat top. The triple-harmonic e.m.f., E_3, is nearly half the fundamental, E_1, in this case. From this peaked wave E may result an increased insulation strain, but a decreased hysterisis loss. The e.m.f. on the transformer is higher than the line e.m.f. divided by $\sqrt{3}$.

In cases where the neutral is not grounded, these harmonics of electromotive force appear as potential difference between neutral and ground. The neutral of Y-connected three-phase transformers therefore is not at ground potential, but may have a considerable potential difference against ground, of triple frequency: the third harmonic, E_3 Fig. 11, which is generated be the magnetic cycle of the transformer.

With a grounded neutral; that is, zero potential difference between neutral and ground, but no other ground on the system, the triple harmonic of exciting current still cannot flow, and the potential difference in the three transformers still contains a third harmonic. Since all these triple harmonics are in phase with one another, it means that all three lines rise and fall simultaneously, or in synchronism with one another against ground, or a triple-frequency voltage appears between the three lines of the three-phase system and the ground, which may have a fairly considerable magnitude as seen in Fig. 11. Suppose now these transformers with grounded neutral feed into a long distance transmission system. We have a circuit from the grounded neutral, over the inductance of the three transformers in multiple, and back to ground over the capacity of the three transmission lines against ground, with a triple-frequency impressed e.m.f., the third harmonic generated in the transformers. There is a high frequency e.m.f., in series with inductance and capacity. Such a combination may, under unfavorable conditions, be serious in originating surges in the system, against ground, of more or less destructive voltage. But even if no serious high potential phenomena occur, the rise and fall of the whole system at triple frequency may give electrostatic induction on neighboring circuits, as telephone lines, etc. Suppose we ground the neutral of the step-down transformers also, and connect their secondaries in delta. Then the triple-frequency electromotive force disappears and the triple-frequency current flows over the ground and circulates in the secondary delta of the step-down transformers. We have then in the system a triple-frequency current which flows over all three lines in parallel and back over the ground; and while triple-frequency electrostatic induction disappears there appears electrodynamic induction.

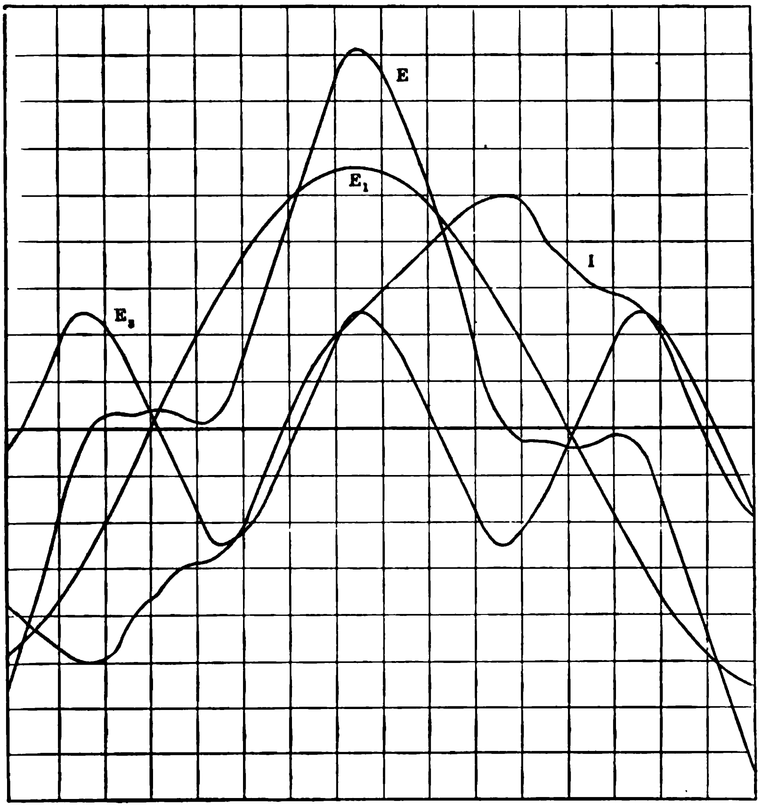

Fig. 11.

Similar phenomena also occur with alternating-current generators. In a three-phase generator with the three coils Y-connected, if there is a triple-frequency electromotive force in each phase, a potential difference of triple frequency exists between neutral and ground, or, with grounded neutral, between the three lines and ground. These electromotive forces are in series short-circuited upon themselves, in the three-phase delta-connected generator. There is, however, a very essential difference between this case and the corresponding case of the transformer. In the case of transformers, we can only get the triple-frequency component of the exciting current; that is, the current which can flow between neutral and ground, or circulate locally in the delta, is limited. With a generator, it is a short-circuit current of the induced electromotive force of triple frequency. Such currents circulating in the windings of delta-connected generators were observed years ago. In many cases they may have been attributed to abnormally great hysteresis losses, and escaped attention. In the Y-connected generator, you may have triple-frequency electromotive forces in the phases which do not appear in the terminal voltage, and give a triple-harmonic e.m.f. from the neutral against ground, and if we get a path for this triple harmonic, we may get currents which in this case are not merely two or three per cent. of the full load current—the triple-frequency component of the transformer exciting current—but may be full-load current or more. If the phase relation of the triple-frequency harmonic with the fundamental is the same in all generators of the system there would be no current in the neutral. If we run two machines at different excitation, one higher and the other lower, then a current flows between the two machines which is a wattless current, magnetizing the under-excited and demagnetizing the over-excited machine. The terminal voltages are not quite in phase with the induced voltage, but in phase with each other, since the machines are connected together. The triple-frequency voltages so give a resultant, and thus a current over the neutral, which may reach very high values. If we have two generators, one having a triple-frequency e.m.f., we get the same phenomenon of a triple-frequency current; but this current is not limited and may occasionally reach values comparatively high, and that is why it is not safe freely to ground the generator neutrals. If the generators are to be grounded, they should be grounded through a resistance limiting the neutral current, or they must have practically the same wave shape and the excitation must be kept practically alike in each generator.

Philip Torchio: I wish to ask Mr. Steinmetz about the third harmonic short circuit between three-phase generators Y-connected with the grounded neutral. One of the largest companies in New York tried at the start to operate all the generators engine-driven with the neutral grounded, and they found a large short-circuit current between the neutral of different generators, evidently due, as explained by Mr. Steinmetz, to the third harmonic. In two other plants operating exclusively with turbine-generator sets, no short-circuit current of the neutral has been manifested by the ammeter, all the neutrals of the Y-connected generators being dead grounded. Will Mr. Steinmetz explain why the engine-driven generators give the third harmonic short-circuit current, while the turbine-driven generators do not give such current?

Chas. P. Steinmetz: I think I can explain that. The turbine generators were all alike, running with identical wave shapes at equal excitation. I do not know what station is referred to, but if I guess correctly, in the same station some larger turbine-generator sets were afterward installed, and between the old machines and the new ones, very considerable currents were found over the neutral. The question is, whether the triple harmonics are identical and have the same phase, or whether they are not identical and have not the same phase.

W. S. Franklin: It is not very often that any of us gets a chance to find fault with what Dr. Steinmetz says, but there is one thing which he mentioned to-night which I wish to criticize, and that is the idea of a hysteresis loop connected with a rotating disc when the flux remains at one constant value; unless, indeed, Dr. Steinmetz means to compare the magnetizing current in the horizontal coil with the vertical component of the magnetism.

Two or three points now which are chiefly of interest in matters educational. In the first place I want to call attention to the use of the word ' sinusoidal." In the study of mechanics the word " harmonic " has come into almost universal use for designating that type of motion which is exemplified in the swinging of a pendulum. That is sinusoidal motion. We should adopt the term harmonic, and speak not of sinusoidal, but of harmonic currents and harmonic electromotive forces.

Another point concerns the assumption which is made in all alternating-current treatises as to the harmonic character of electromotive forces and currents generated by alternators. It seems to me that it is a false idea which many people have gotten into, that this assumption places a limitation on the theory of alternating currents, for this reason: given an alternator which develops an electromotive force of any complicated wave-shape whatever, and let it be required to determine the current produced by the electromotive force. This problem resolves itself into a series of problems, each one of which is an ordinary simple harmonic alternating-current problem. The first thing to be done is to resolve the electromotive force into harmonics, and then treat each harmonic electromotive force by itself, and discuss the currents produced. If you limit yourself to the fundamental, you have only solved one problem of the series, ignoring all the others.

In regard to the matter of the magnetizing current, I will call attention to one point, and that is, that we have had two meanings attached to the term angle of hysteretic advance; one by Dr. Bedell and one by Dr. Steinmetz. I do not think, however, that it is important that this term should be standard, because we do not use it very much.

In regard to the representation of harmonic electromotive forces and currents in vector diagrams, I wish to call attention to two distinct ideas that are involved. First, there is the idea of representing what actually takes place in a circuit; in this case the rotating vectors represent the successive instantaneous values of current and voltage; that is, they represent the actual physical facts. Secondly, there is the idea of getting geometrical representations of formulas. This second idea seems to be in Dr. Bedell's mind. Thus a given current of fundamental frequency and given current of triple frequency when superposed give an effective current which is equal to the square root of the sum of the squares of the two; therefore Dr. Bedell chooses to represent the triple-frequency current by a line at right angles to the plane of the fundamental diagram. That is all very well, but we must keep in mind that we are using the diagram merely as the picture of a formula and not as a representation of physical actions. For my part I prefer to limit the vector diagram to the representation of physical action and I always use the idea of a rotating vector for representing in the students' mind the successive instantaneous values of current and voltage.

Frederick Bedell: Professor Franklin's remarks well accord with our own views. It has been brought out in the paper that at least two definitions may be given to the angle of hysteretic advance, these corresponding to the angles α and ψ as used by the authors; Professor Franklin emphasizes this. The relation between α and ψ is given in Fig. 16, and our purpose has been to distinguish clearly between them. Professor Franklin will find that his definition is our α, the value as found by measurement with ammeter, voltmeter, and wattmeter.

Professor Franklin also expresses our views in regard to the significance of the geometrical construction. It is merely a picture which helps us to understand some relations. These relations we get more clearly in the diagram, but the diagram is not in any wise a physical representation of the facts.

W. S. Franklin (by letter): Two additional points were touched upon in my discussion, namely, (a) in connection with Dr. Steinmetz's reference to Froelich's equation to the B and H curve I stated it as my opinion that there are certain physical relations which are essentially irrational and erratic, that such relations can never be formulated in the sense in which Kepler formulated the relations involved in planetary motion, and that we ought to give up an idea which seems to be quite prevalent— the idea that way back somewhere in the region of ideality, wherever that may be, there is a formula that will reduce any physical relation to a rational basis. I discuss this point rather fully on page 285 of Vol. XX of the Institute TRANSACTIONS. (b) In connection with Dr. Steinmetz's reference to the influence of vibration on the B and H curve, I called attention to a paper of mine* in which vibrations were used in the determination of what I call a normal curve of B and H.

C. P. Steinmetz (by letter): (1) Regarding the angle of hysteretic advance α, I always define this as the phase-angle between the equivalent sine wave of exciting current and the equivalent sine wave of electromotive force induced thereby; that is, the angle given by ammeter, voltmeter, and wattmeter reading, after correcting for the I^2R (which is best done by using an exploring coil for the potential circuit of wattmeter and voltmeter). In the hysteresis motor referred to in the discussion, it can be shown that the space-angle between the resultant magnetic flux and the magnetomotive force equals the angle of hysteretic advance of phase of the exciting coils, and this space-angle was therefore referred to as the hysteresis angle.

(2) In general. I fully agree with Professor Franklin regarding empirical equations. I do not consider the parabolic law of magnetic induction:

$$B\text{-}H = \frac{H}{\alpha + bH}$$

as an empirical law, however, but rather as a rational equation approximating the B-H curve, and the deviations of the induction curve from this equation as due to secondary phenomena not included in the equation: molecular magnetic friction, which causes a deviation, especially at lower densities; lack of homogeneity, especially noticeable at intermediate inductions (most pronounced in cast iron), etc.

If I remember correctly, Fröhlich proposed this equation, not from experimental data—which at his time were hardly sufficient—but by the following reasoning: magnetic induction in iron, etc., reaches an absolute limiting, or saturation value. This has been proved by Ewing for the ‘ metallic magnetic induction ” B-H. When approaching magnetic saturation, the magnetic permeability must therefore decrease, and it is reasonable to assume that the permeability is proportional to the remaining magnetizability of the iron, or to the difference of the induction B from its saturation value S. This gives Fröhlich's equation:

$$\mu = \alpha\,(S - B)$$

or, since $\mu = \frac{B}{H}$:

$$\frac{B}{H} = \alpha\,(S - B)$$

Physical Review, Vol. VIII, pages 304-309.

$$B = \frac{H}{\frac{1}{\alpha S} + \frac{H}{S}} = \frac{H}{A + BH}$$

or, substituting the reluctance:

$$\rho = \frac{1}{\mu} = \frac{H}{B}$$

it gives Kennelly's equation:

$$\rho = \frac{1}{\alpha S} + \frac{H}{S} = C + D H.$$

These equations obviously do not apply to the total induction B, but to $B_0 = B - H$: the difference, however, becomes noticeable only at very high magnetomotive forces.

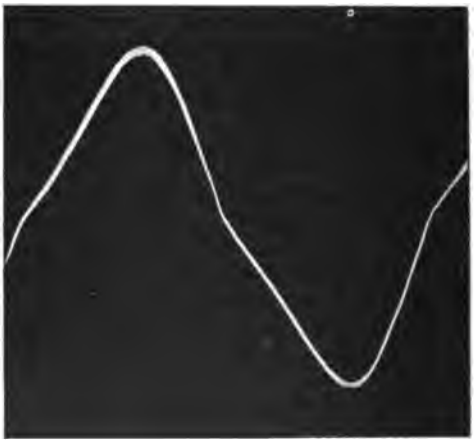

FIG. 1.

Harold Pender (by letter): The effect of iron in distorting the wave-form of current and pressure is of particular importance in determining the energy-loss in small samples of iron by the wattmeter method. In this method of measurement the maximum flux density is usually calculated from the effective pressure measured by a voltmeter across the terminals of the magnetizing winding on the sample; or the induced pressure in a secondary winding on the sample may be measured, this method eliminating the resistance-drop in the magnetizing winding.

In general the maximum flux density is proportional to the average value of the induced electromotive force over half a cycle; only in case of a sine wave of induced electromotive force is the flux density proportional to the effective value. Could a sine wave of electromotive force be impressed directly on a magnetizing winding without resistance, the counter electromotive force of induction would also have a sine form, and would therefore be proportional to the effective pressure determined by

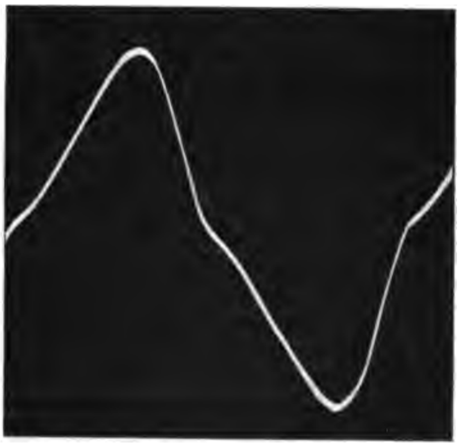

Fig. 2.

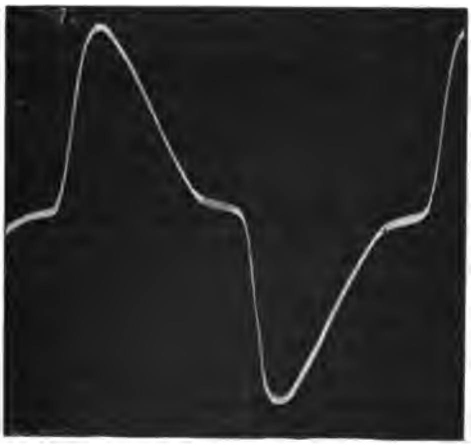

Fig. 3.

the voltmeter. This, however, is practically impossible, as there is always more or less impedance in the primary circuit external to the magnetizing coil; namely, that of the instruments in the circuit, as well as that of the transformer for stepping down the generator pressure to a sufficiently low value to apply to the sample under test. In fact, even when the utmost precautions are taken to keep the impedance of the circuit exterior to the magnetizing coil as small as possible, this external impedance may be the controlling factor in the circuit, particularly for high values of the flux-density, and corresponding low values of the permeability. As this external impedance is practically constant under such conditions, the current in the magnetizing coil may have very nearly a sine form, and consequently produce a much distorted wave of induced electromotive force in the sample.

The accompanying oscillograph records give the pressure-waves under various conditions induced in a secondary winding on a sample of iron weighing about 6 lb. The sample was built up of punchings in the form of a hollow square 5 in. outside, 3 in. inside, each sheet 0.14-in. thick. The magnetizing coil had 20 turns. The total resistance of the circuit between generator and sample was about 0.75 ohm, of which 0.3 ohm was in the instruments in the circuit and 0.45 in the step-down transfomer (one-half a kilowatt, 20 to 1 ratio). The magnetizing coil itself had practically no resistance. The source of pressure was a small 110-volt motor-generator, giving a sine-wave electromotive force.

Curve 1 is for 25 cycles and a maximum flux-density of 6,850 lines of induction per square centimeter.

Curve 2 is for 25 cycles and a maximum flux-density of 11,300

Curve 3 is for 25 cycles and a maximum flux-density of 12,800.

A sine-wave of pressure at the terminals of the magnetizing coil would have given flux-densities of 7,000, 12,000 and 15,000 lines respectively.

The following table gives for another sample the flux-densities calculated on the basis of a sine wave electromotive force and the true flux-densities determined from the average values of the electromotive force wave:

B Calculated on basis of sine wave.	True B		Ratio of True B to Calculated B.	
	60 Cycles.	25 Cycles.	60 Cycles.	25 Cycles.
4,000	4,000	4,000	1.00	1.00
7,000	6,800	6,500	0.97	0.93
10,000	9,400	9,100	0.94	0.91
12,000	11,000	10,600	0.92	0.88
15,000		12,200		0.81
17,500		13,200		0.76
20,000		14,100		0.71

A. Henry Pikler (by letter): Professor Bedell's paper gives the impression that the hysteresis loop is the only cause of the distortion of alternating-current wave-forms. This is not so. The distortion is primarily due to the change in permeability during one cycle of magnetism; the hysteresis is only accidental.

Mr. Steinmetz indicates how the induced electromotive force wave form will become distorted in a transformer by magnetizing it with a sine wave current. To sustain this contention, I refer to my oscillograms taken in June, 1903,* There it is shown that a constant transformer terminal voltage can be maintained by various forms of magnetizing-current waves which, as they become more and more sinusoidal will make the transformer electromotive force wave take the shape of the previously distorted-current wave.

***Electrical World and Engineer*, 1903, Vol. XLII, No. 6, p. 218.

DISCUSSION ON "EFFECT OF IRON IN DISTORTING ALTERNATING-CURRENT WAVE-FORM", AT PITTSBURG BRANCH, OCTOBER 9, 1906.

S. P. Grace: The sounds of the human voice are not by any means pure tones. In a single sound will be found what we may call the fundamental tone or that of the lowest frequency and, in addition, the harmonics produced by the partial vibration of the vocal chords and the resonating air of the throat and mouth. In telephone transmission the frequencies which are important have a wide range. The lowest are those of the low voice, probably none below 100 periods per second, and ranging upward to 1500 periods per second.

When induction-coils containing iron were introduced into the telephone circuit, it was found that the character of the speech was very much altered. This is explained by the introduction of new harmonics in new phases on account of the hysteresis in the iron. Some time ago, in a conversation with Mr. Tuttle on the subject of harmonics introduced by hysteresis, I suggested that the energy expended in the dielectric between cable conductors might possibly be of hysteretic character, thus introducing harmonics. These must of necessity be small, but some investigations will probably be made to determine their magnitude. The subject of the higher harmonics is, therefore, a live one with telephone engineers.

H. B. Tuttle: The instantaneous current at some one point of the wave was found to be greater than the maximum of the same mean-effective current flowing in a sine wave (without iron). The curves show that this difference is much more marked in the case of those hysteresis loops which indicate the higher saturation in the iron. Thus it would seem that the quantity of the iron rather than the quality is the determining factor.

S. M. Kintner: Replying to the question as to whether or not some advantageous use could not be made of the current wave distortion which made it quite abrupt in the construction of induction-coils for gas-engine ignition, I must say that I do not hope for any success along these lines. I look on a spark-coil as a device capable of having a certain amount of potential energy stored in its magnetic field. This amount of energy can be suddenly converted into kinetic energy by the sudden interruption of the exciting current, and thus voltages of considerable value are produced in the secondary circuit. Mr. Tuttle's paper relates only to alternating-current work, and while the current wave-form may have considerable distortion, the magnetic wave-form will be practically the same as that of the voltage impressed.

The fact that the voltage wave-form, and consequently the magnetic wave-form, can be seriously affected by the use of resistance in series with the primary circuit is quite frequently overlooked, with the result that serious errors are caused in the measurement of iron-loss; and quite disastrous results follow the employment of resistance in the primary circuit of testing transformers which are being used to make dielectric tests on electrical apparatus. The resistance has a tendency to peak the voltage wave.

Regarding the flow of idle currents to ground in a three-phase, star-connected, grounded neutral system, it may be of interest to mention that this is true not only in circuits having the third harmonic but also those having the ninth, fifteenth, twenty-first, etc.

A. W. Copley: In the course of some experiments with the oscillograph, some curves were taken that show clearly the distortion of the voltage wave of a transformer when a sine wave of voltage is impressed upon the primary with a resistance in series with it. A non-inductive resistance was connected in series with the primary of a transformer and a sine wave of voltage was impressed upon the two in series. The voltage across the primary was about 15% lower than the total impressed voltage.

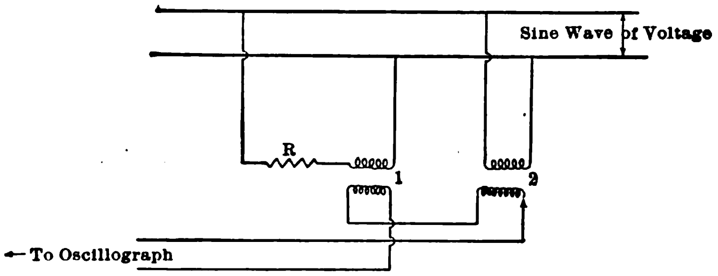

Fig. 1.

A second transformer with numerous taps on its secondary was connected across the same mains as the first transformer, and the secondary turns were adjusted so as to give the same voltage in amount as the secondary voltage of the first transformer. The connections are shown in Fig. 1.

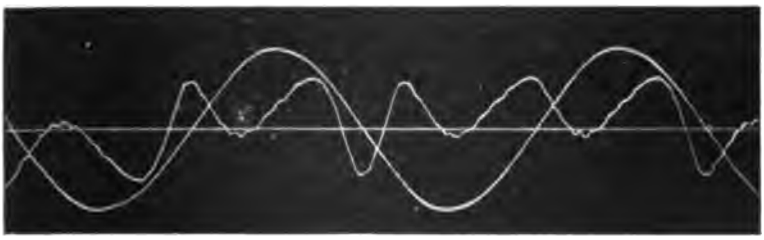

Fig. 2.

In both transformers the secondary voltages will be of substantially the same wave-form as the primary voltages. In the first transformer the voltage wave-form was distorted on account of the presence of the resistance in the primary circuit. The resistance tends to smooth out the harmonics in the current wave-form, and this magnetizing current in the transformer reacts on the voltage of the transformer, introducing harmonics into it. On the second transformer the voltage wave-form will be the true sine wave impressed on the primary.

These two voltages, equal in amount but a little out of phase with each other, were connected in opposition to each other; the result was a low voltage consisting of the out-of-phase component of the main frequency and all the harmonics in the voltage of the first transformer. This wave is shown in Fig. 2. The sine wave shown is the total impressed voltage.

FIG. 3.

To remove the out-of-phase voltage of the main frequency, the phase of the voltage in the first transformer was shifted by the introduction of an inductance in series and a resistance in parallel with the primary. The connecting in opposition of the two secondaries then gave the curve shown in Fig. 3, which shows that the main frequency is almost eliminated and only the harmonics remain.

*A paper presented at the 210th meeting of the
American Institute of Electrical Engineers,
New York, September 28, 1906.*

THE CURRENT TRANSFORMER.

BY KENNETH L. CURTIS.

The current transformer, although mentioned but briefly in electrical literature, is one of the most indispensable of meter auxiliaries. By means of it currents of any magnitude may be measured with accuracy with the smallest of instruments. It enables us to use ammeters and wattmeters in circuits of the highest voltages. By the use of current transformers of different ratios we can use meters of the same size and capacity in circuits of widely varying power and voltage, thereby greatly facilitating the calibration and maintenance of the instruments.

The use of transformers in connection with alternating-current ammeters and wattmeters is absolutely necessary in either of the following cases: first, when the voltage of the circuit is so high as to render it unsafe to connect the instrument directly into the circuit; secondly, when the current to be measured is greater than the capacity of the instrument, and conditions prevent the use of a shunt. In the first instance the transformer insulation is made sufficient to protect the instrument from the high-voltage circuit. In the second case the ratio of turns is made such that the current through the instrument is within its capacity. In nearly all cases of alternating-current measurements one or both of these conditions are met with.

The current transformer, like all other transformers, consists of an iron magnetic circuit interlinked with two electric circuits. The primary is connected in series with the line, the current of which is to be measured, and the secondary is connected to the instrument terminals by leads of low resistance. With these connections it is evident that the meter-reading will go up and down with the line current; and although the ratio of the meter-reading to the line current may not be the same at all times, any one value of the current will always give the same meter-reading. If the instrument were in all cases calibrated in conjunction with the current transformer with which it is to be used, the only points necessary to consider in the design of the transformer would be the heating and insulating. In well-designed current transformers, however, the ratio of primary to secondary current is nearly constant for all loads within desired limits, so it is not necessary to test the instrument with its own transformer except when it is to be used for refined measurements.

In order to predetermine the behavior of a transformer it is in general necessary to know: first, the resistances and reactances of the primary and secondary windings of the transformer and of the external secondary or load circuit; secondly, the amount and power-factor of the exciting current at the various operating flux densities in the transformer core.

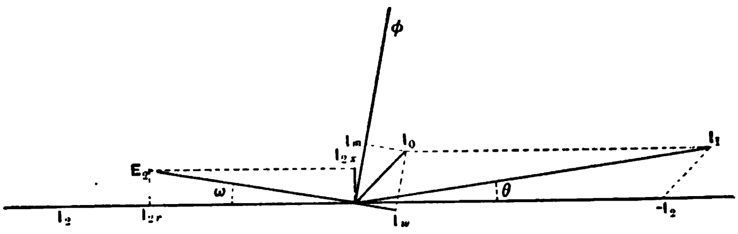

FIG. 1.

In the case of the current transformer, while it is desirable to keep the primary resistance and reactance as low as possible to prevent undue loss of energy, the behavior of the transformer is not affected by their magnitude, as the secondary current depends only on the ampere-turns supplied to the core by the primary winding.

The factors which enter the discussion of the current transformer are shown in the diagram, Fig. 1.

I_2 is the secondary current.

r and x are the resistance and reactance of the secondary circuit.

$E_2 = I_2 r - j\, I_2 x$ is the voltage consumed in the secondary circuit.

ϕ is the total flux of the transformer; it is proportional to E_2 and is 90° ahead of E_2.

I_0 is the exciting current consisting of the wattless component I_m and the power component due to hysteresis and eddy currents I_W.

$I_1 = I_0 - I_2$ is the total primary current.

ω is the angle between the secondary e.m.f. and current.

$$\cos \omega = \frac{r}{\sqrt{r^2+x^2}} \qquad \sin \omega = \frac{x}{\sqrt{r^2+x^2}}$$

θ is the angle between the primary current and the reversed secondary current.

$$\cos \theta = \frac{\text{horizontal component of the primary current}}{\text{primary current}}$$

k = ratio of transformer, is the factor by which the instrument reading (I_2) must be multiplied to give the primary current.

For ammeters, $k = \frac{I_1}{I_2}$.

For wattmeters, the ratio k is nearly $\frac{I_1}{I_2}$, but is influenced by the angle θ. The exact effect of the angle θ depends on the power-factor of the load measured. If the power-factor is $\cos \frac{\theta}{2}$ lagging current it is evident that the wattmeter and ammeter ratios of the transformer will be the same, for the effect of the angle θ will be to cause the meter current to lead the line electromotive force by $\frac{\theta}{2}$ thereby giving the same reading as though it led by the same amount. For lagging current power-factors of less than $\cos \frac{\theta}{2}$ the wattmeter ratio will be less than the ammeter ratio; for all other values it will be greater.

Given r, x, I_m, and I_W, to determine I_1 and θ.

The horizontal and vertical components of I_1 can easily be obtained from Fig. 1 as follows:

	Power Component.	Wattless Component.
$-I_2$	$I_2 \cos \omega$	$I_2 \sin \omega$
I_0	I_W	I_M
I_1	$I_2 \cos \omega + I_W$	$I_2 \sin \omega + I_M$

$$I_1 = \sqrt{(I_2 \cos \omega + I_W)^2 + (I_2 \sin \omega + I_m)^2}$$

$$\cos \theta = \frac{I_2 + I_m \sin \omega + I \omega \cos \omega}{I_1}$$

From the foregoing it will be seen that if we can determine the quantities r, x, I_m, and I_W we can readily predetermine the behavior of the transformer.

Owing to the low magnetic flux densities at which the transformer works, the values I_m and I_W can not be measured with the ordinary available instruments; r is readily obtained, but x is so low as to require special means of measurement. These quantities will be taken up in order, and the means used to determine them discussed.

(1) *The Determination of the Value of x*: This quantity is made up of the inductance of the meter and leads, plus the self-induction of the secondary of the transformer.

The inductance of measuring instruments is so small as to present serious difficulties in its accurate determination. After several unsuccessful attempts at bridge-methods the following means was hit upon.

With connections as in Fig. 2, L_1, L_2, and C are adjusted so as to give a sine-wave current of desired value through x the unknown inductance.* A hot-wire voltmeter of extreme low range is connected across x. Simultaneous readings of the voltmeter and ammeter are taken. The voltmeter is non-inductive, so its current I_V is in phase with the voltage E across x, and both E and I are known from the reading of the instrument. Consider the portion of the circuit containing the un-

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*Ryan, Cathode Ray Wave Indicator, TRANSACTIONS A. I. E. E., Vol. XXII.

known impedance and the hot-wire voltmeter, Fig. 3. x is the unknown reactance. R_v is the resistance of the hot-wire voltmeter and E its reading. I_t is the total current read on the ammeter in Fig. 2. In branch circuit $x\,R_x$

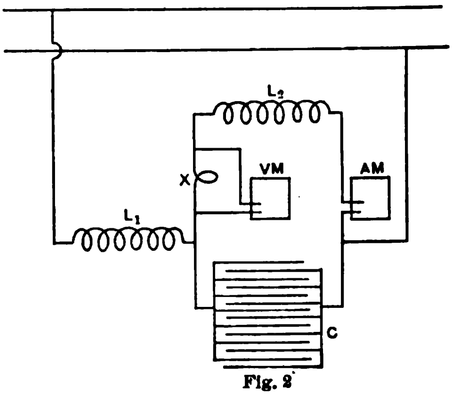


Fig. 2

(1) $E = I_x \sqrt{(R_x)^2 + x^2}$ in which both I_x and x are unknown. Square (1) and divide by R_x^2.

(2) $$\frac{E^2}{R_x^2} = I_x^2 + \frac{I_x^2\,x^2}{R_x^2}$$

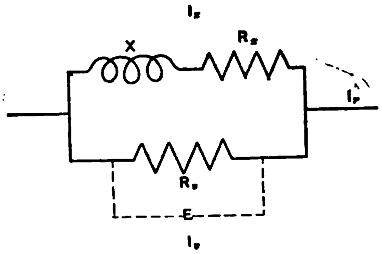


Fig. 3

Equation (2) is represented graphically in Fig. 4. Angle $\theta = \tan^{-1}\frac{x}{R_x}$ is the angle between I_x and E and hence between I_x and I_v.

The current I_t is the vector sum of I_v and I_x.

(3) $$I_t^2 = I_v^2 + I_x^2 + 2\,I_v\,I_x \cos\theta.$$

In the quadrant in Fig. 5, $O\ E$ is taken as the direction of the electromotive force E. I_t is taken as radius, and $O\ A = I_v$ is laid off in the direction $O\ E$. At some point B on this quadrant the distance $A\ B = I_x$ and the angle θ the angle between I_x and I_v.

By superimposing the semicircle as Fig. 4 on the quadrant of Fig. 5 so that the points $A\ A$ coincide and $\frac{E}{R_x}$ has the direction $O\ E$, the point of intersection B gives the value of I which satisfies both (2) and (3). x is obtained by inserting this value of I_x in (1). This graphical solution is simple and is amply accurate for all purposes.

By this means a number of meters were measured. The values of x in volts per ampere for several of the instruments tested are as follows:

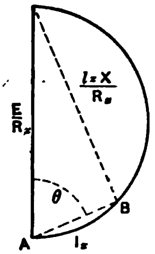


Fig. 4

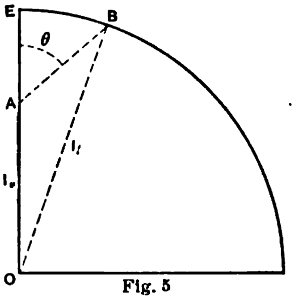


Fig. 5

Five-ampere indicating ammeter	$x = 0.0390$
Three-ampere recording wattmeter	$x = 0.0842$
Two-ampere indicating wattmeter	$x = 0.1205$
Three-ampere indicating wattmeter	$x = 0.2140$
Two-ampere indicating ammeter	$x = 0.2930$

The self-induction of the transformer secondary is too low to be easily measured but can usually be computed from the constants of the transformer.

In the following discussion one of the present commercial types of current transformer will be taken up and its ratio computed by the foregoing theory.

The core is a ring of the dimensions given in Fig. 7.

Weight = 5.422 lb.

Volume = 19.14 cu. in.

116 laminations 0.014-in. thick.
Length of path of flux = 11.78 in.
Area of path of flux = 1.637 sq. in.

Due to symmetry, the only possible path for leakage flux is around each individual conductor as indicated by the dotted line in Fig. 8. The flux set up in this path per centimeter per ampere multiplied by the length of wire in centimeters gives the total secondary leakage flux.

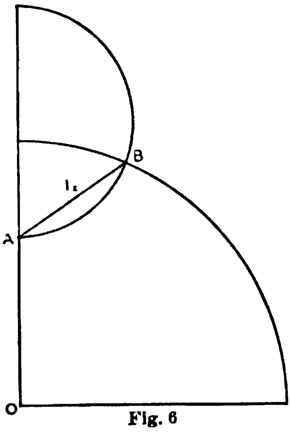


Fig. 6

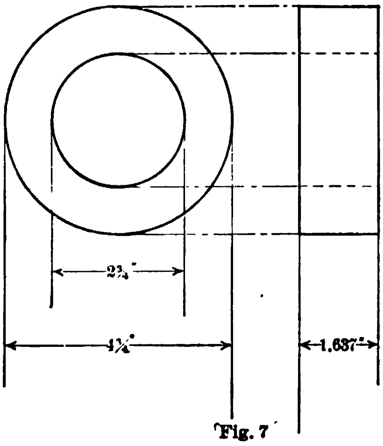


Fig. 7

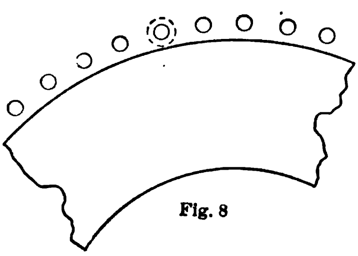


Fig. 8

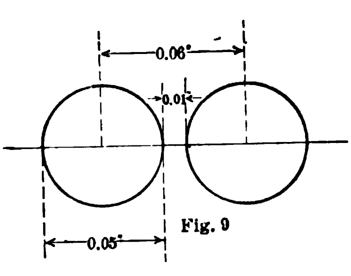


Fig. 9

The secondary winding consists of 300 turns of No. 16 double cotton-covered wire wound symmetrically around the core as close as good insulation will permit. (The rated secondary current is three amperes.)

Diameter of wire = 0.05 in.

Distance between wires = 0.06 in.

$$\phi = \frac{4\pi n I A}{10 l} \qquad I = 1 \qquad n = 1$$

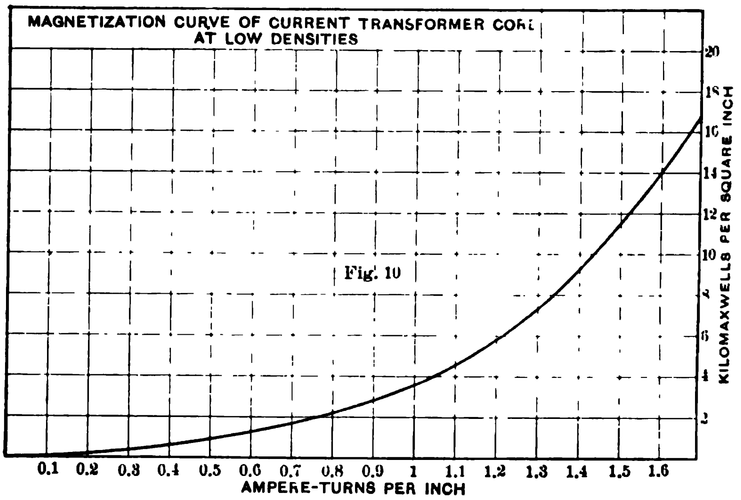

MAGNETIZATION CURVE OF CURRENT TRANSFORMER CORE AT LOW DENSITIES

Fig. 10

$l = \pi \times 0.06 \times 2.54 = 0.479$. A is variable. It is 0.01 in. between wires, about 0.03 in. between wire and core, and several times this value on the side of the wire away from the core. A value of 0.04 is probably large but will be used in this computation.

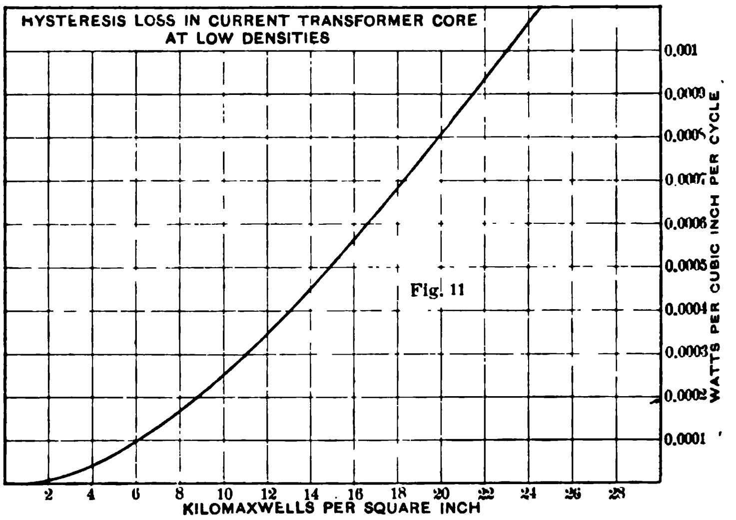

HYSTERESIS LOSS IN CURRENT TRANSFORMER CORE AT LOW DENSITIES

Fig. 11

A in centimeters $= 0.04 \times 2.54 = 0.1016 \therefore \phi = 0.267$ per cm.
Total length of wire = 5410 centimeters.
$\therefore \phi$ total per ampere = 1445.

$$x \text{ in voltage per ampere} = \frac{60 \times 4.44 \times 1445}{10^8} = 0.00385$$

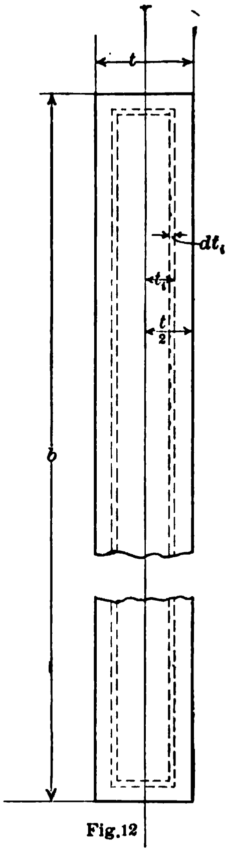


Fig.12

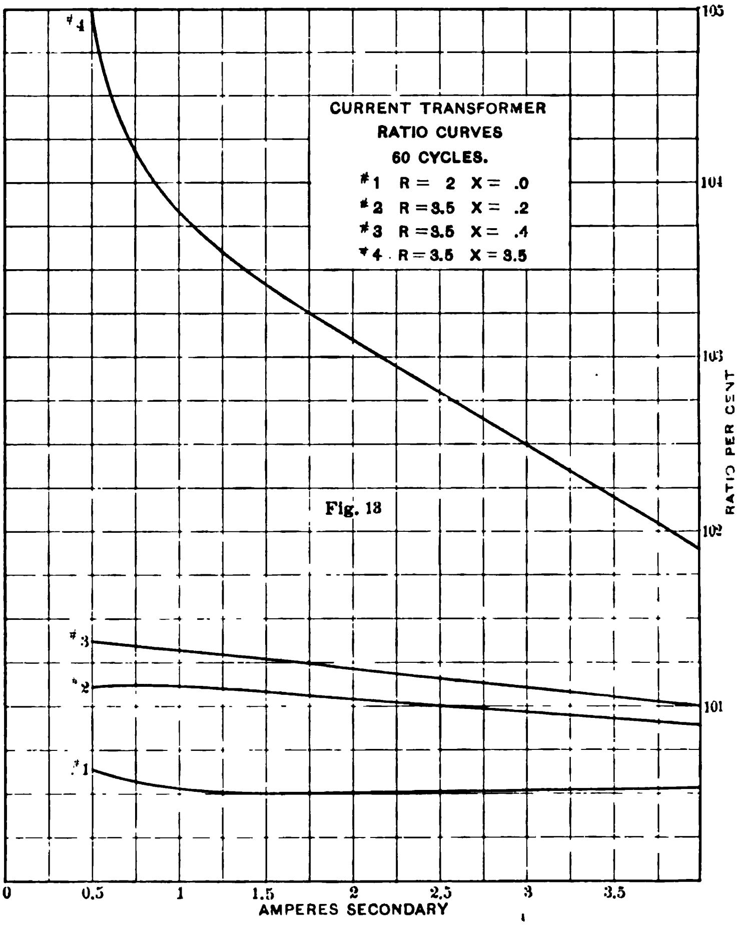
The reactance of the transformer is therefore practically negligible.

The total reactance of the secondary circuit is but slightly greater than that of the meter which for a three-ampere transformer will be from 0.1 to 0.2.

Current transformers are largely used to supply relays for various purposes. The reactance of a relay is high and is variable. The effect of a high reactance on the transformer ratio is shown in the ratio curves, Fig. 13.

(2) The determination of I_m and I_w

As has been stated, the magnetic flux density at which the current transformer works is so low as to render it practically impossible to measure the exciting current and core loss by ammeter and wattmeter. For this reason the magnetization curve Fig. 10, and the hysteresis-loss curve, Fig. 11, of the transformer core were obtained by the ballistic method.



The portion of I_w due to eddy currents was obtained by computing the ampere-turns necessary to compensate for eddy currents in the following manner: the ampere-turns due to eddy currents are numerically equal to the current which circulates in any lamination.

Consider a lamination of width b and thickness t.

The electromotive force generated in a circuit of differential section, Fig. 12, is:

$$E = 2\, t_i\, b \sqrt{2}\, \pi\, B_{max}\, f\, 10^{-8}$$

$$I \text{ per inch in length of laminations} = \frac{E}{R \text{ per inch}}$$

$$R \text{ per inch} = \frac{2\, b\, R_{sp}}{d\, t_i} \qquad R_{sp} = 3.927 \text{ microhms}$$

$$I \text{ per inch} = \int d\, i = \frac{2\, b \sqrt{2\, \pi\, B_{max}\, f}}{2\, b\, R_{sp}\, 10^8} \int_0^{\frac{t}{2}} t_i\, d\, t_i = 0.001415\, B_{max}\, f\, t^2$$

The following table gives the computation of ratios of the transformer under average working conditions. The resistance of the secondary circuit is taken as 3.5 ohms which gives the rated full load of the transformer, 40 watts. The reactance is taken as 0.2. 300 secondary turns, ratio = 1:1, $r = 3.5$, $x = 0.2$, 60 cycles, $\sin \omega = 0.05705$, $\cos \omega = 0.99837$.

I_2	0.5	1	1.5	2	3	4
E_2	1.7528	3.5057	5.2585	7.0114	10.517	14.0228
E_2 per turn	0.005843	0.011685	0.017528	0.023371	0.035057	0.046742
$B = \frac{\phi\text{max}}{A} = 223910 E_2$ per turn	1341	2673	4020	5360	8038	10718
A-T per inch from curve	0.6	0.873	1.056	1.17	1.334	1.461
$I_M = A$-T per inch $\times \frac{11.78}{300}$	0.0235	0.034201	0.04137	0.045836	0.05226	0.057237
I_W (hysteresis) = $\frac{\text{hysteresis watts}}{E_2}$	0.002621	0.00655	0.0102	0.0131	0.01856	0.023258
I_W (eddy currents) = $\frac{A\text{-}T \text{ due to eddy currents}}{300}$	0.001144	0.00228	0.00343	0.00457	0.00686	0.00915
I_W (total)	0.003764	0.00883	0.01363	0.01767	0.02542	0.032408
I_1	0.50563	1.0113	1.5164	2.0208	3.0288	4.036
Ammeter ratio	1.01126	1.0113	1.0109	1.0104	1.0096	1.009
$\cos \theta$	0.9989	0.9994	0.9997	0.9997	0.9998	0.9999

The curves in Fig. 13 show the ratios from 0.5 to 4 amperes for several values of resistance and reactance. These curves were computed from the constants of the instrument. The computations for curve 2 are given in the foregoing table. Curve 1 shows the effect of resistance alone on the ratio. Curves 2, 3, and 4 are the actual working curves of the instrument and so closely resemble the laboratory and factory tests on this type of transformer that they could easily be mistaken for the actual tests.

From the foregoing it will be seen that the factor which prevents a constant ratio of secondary to primary current for all loads is the exicting ampere-turns. The smaller these are in proportion to the total ampere-turns of the transformer and the lower the power-factor of the exciting current the more nearly will we approach a constant ratio.

Assuming the secondary to have as low resistance and reactance as is practicable, to obtain the best results we must make the magnetic circuit so as to have as low values of reluctance, hysteresis, and eddy currents as possible. That is to say, if the secondary has as low resistance and reactance as is practicable the best current transformer will be the one containing the most iron of the best quality in the form of the thinnest laminations.

DISCUSSION ON "THE CURRENT TRANSFORMER," AT NEW YORK, SEPTEMBER 28, 1906.

L. T. Robinson: We have recently been working with current transformers, using a somewhat different method from that given by the author of the paper; that is, instead of determining the exciting current and the internal losses in the transformers by means of a ballistic galvanometer, we have, by means of sensitive alternating-current dynamometers, determined these values directly, and have been able to get a fair agreement between these values and those obtained with the ballistic galvanometer. In this connection the effect of wave distortion is quite prominent. In making these measurements, if a resistance is included in series with the primary of the transformer under test, the impressed electromotive force on the transformer itself is distorted, and the current wave is distorted. Under these conditions it is rather difficult to determine, not just what the exciting current is but what it would be under the conditions of use.

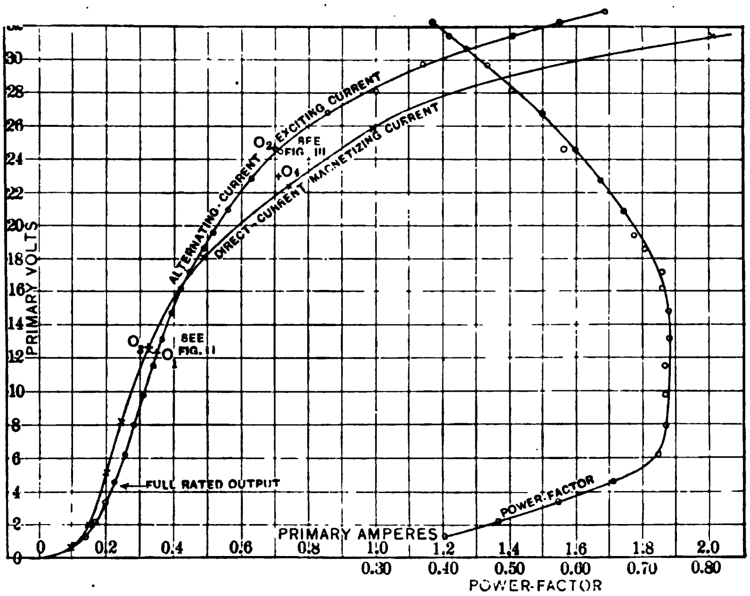


FIG. 1.

Fig. 1 shows measurements which have been made by both methods; these indicate that even with the small resistance losses in these delicate instruments, in comparison with the very small losses in transformers of this kind, the distortion is appreciable although not sufficient to destroy the value of the measurements. The principal effect at high densities is much above the full rated capacity of the transformer, which point is indicated in the figure. In the experiments, the resistance and inductance of the circuit containing the instruments was kept constant throughout the limits of the test. The measurements at higher densities can be made with much less impedance in circuit, and hence with very much less distortion.

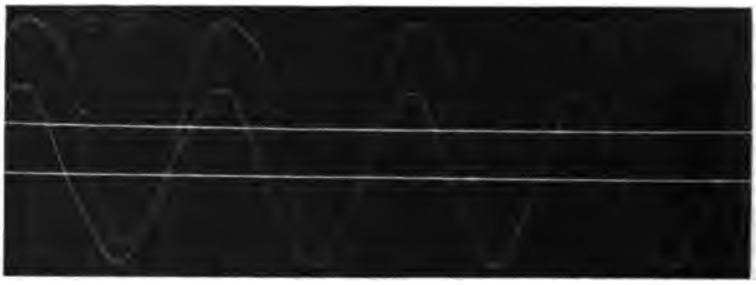


Fig. 2.—Upper curve exciting current 0.25 amp. $\sqrt{mean^2}$. O_1 on Fig. 1.
Lower curve potential across primary.
In series with trans. primary R = 10.0 and L = 0.01908.

Under the test conditions, several records have been taken of the distorted waves Figs. 2, 3, 4, and 5, which may be of interest both in connection with the paper on transformers, and in connection with the discussion on wave distortion which has already taken place.

Fig. 2 gives potential wave across primary of transformers and exciting-current waves corresponding to point O_1 on Fig. 1.

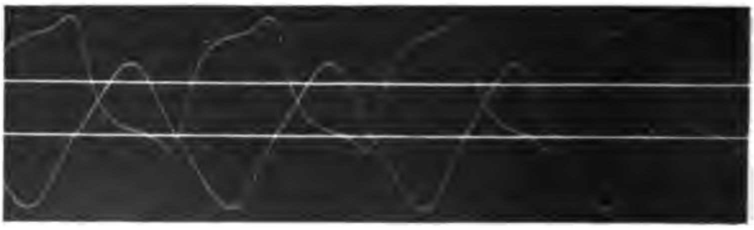


Fig. 3.—Upper curve exciting current 0.5 ampere. O_2 on Fig. 1.
Lower curve potential across primary.
In series with trans. primary R = 10.0 and L = 0.01908.

Fig. 3 C. D., gives same at point O_2.

Figs. 4, 5, 6, and 7 at points higher up on curve.

The time has not been available to gather from these oscillograms more than qualitive information tending to show that the effect of wave distortion is of little account at lower values of magnetization, through the range where the transformers are normally used.

Two points, O_1 and O_2, have been corrected for distortion of wave shape, giving O_3 and O_4.*

In connection with this subject the phase-angle between the primary and secondary currents is in some cases of as great importance as the ratio of the transformer, especially when wattmeters are to be used and the power-factor of the circuit to be tested is low. Exciting current has also been obtained by determining with considerable accuracy the phase-angle and the ratio of currents, and then deducing from this ratio of currents and the phase-angle between the primary and secondary, the exciting current. This can be made to correspond under reasonable limits with the exciting current determined directly by dynamometer instruments.

FIG. 4.—Upper curve exciting current 0.5 ampere. Lower curve potential across primary. Same as Fig. 2.
In series with trans primary R = 10 and L = 0.00164.

FIG. 5.—Upper curve exciting current 1 ampere. Lower curve potential across primary.
In series with trans. primary R = 10 and L = 0.00164.

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*Observed alternating current volts X $\frac{1.11}{\text{form-factor}}$ = corrected volts.

Observed alternating-current amperes X amplitude-factor = corrected amperes.

Reference.—E. Gumlich and P. Rose, *Electrotechnische Zeitschrift*, January 1, 1905, p. 503.

In connection with this measurement of the phase-angle, it may be of interest to explain what we have been doing. The method is very simple and satisfactory and was developed by my assistant, Mr. O. Holz. Fig. 8 A, shows the transformer primary in which is included the resistance R. The transformer secondary working on the load as shown, has included in its circuit the resistance *r*. Connected with the suppiy circuit is a phase-shifting device to which in turn is connected the fixed coil of one of the sensitive dynamometers to which reference has been made. The moving coils of the dynamometer are now connected to *R* by means of a double-throw switch, and using the phase-shifter, adjust to a 90-degree relation (*O* deflection) between the current in the fixed coil and the current in the moving coil. The instrument is now sensitive to a change in angle of either one of the currents. The moving coil of the dynamometer is quickly transferred by means of the switch to resistance *r*, and a deflection is obtained. By taking into account resistances *R* and *r*, the current value in the primary and

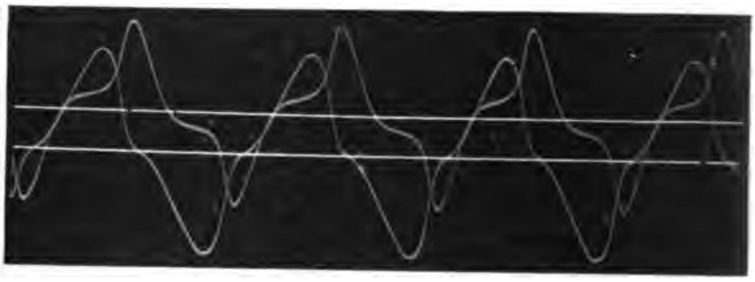

FIG. 6.—Upper curve exciting current 2 amperes. Lower curve potential across primary.
In series with trans. primary R = 10 and L = 0.00164.

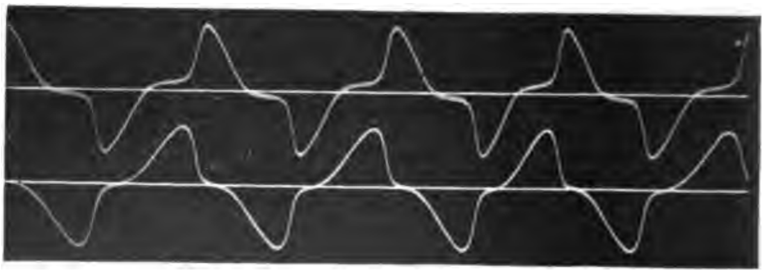

FIG. 7.—Upper curve exciting current 3 amperes. Lower curve potential across primary.
In series with trans. primary R = 10 and L = 0.001224.

the secondary sides of the transformer, and the current in the fixed coils, the angle between the current flowing through *R* and *r* is readily deduced. The following formula may be used:—

$$\text{Sin}\ \theta = \frac{\text{wattmeter reading expressed in watts}}{I_f \times ri_s}$$

I_f = current in fixed coil.
ri_s = volts drops in resistance *r*.

This test is somewhat more readily accomplished using two reflecting wattmeters, as shown in Fig. 8 B; in fact it is usually made in this way.

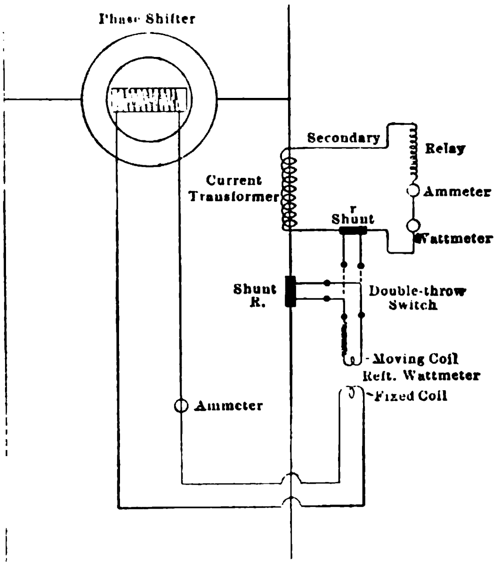

FIG. 8a.

It is at times useful, in going along with work in which transformers are used, to know the practical limit of the angle between the primary and secondary currents. Using the diagram in about the same way as the author has drawn it, we have I_2, Fig. 9, secondary current, and if there is no reactance in the secondary it would lie in the direction E_2, but the cases in which there is no secondary reactance are unusual. The appearance of it will be more like the figure. The exciting current, I_0, even under the most unfavorable conditions where the energy component of the core loss is small, would be about as shown. In practical cases it is quite safe to consider that the angle *C* would not be less than 135 degrees, in which case the effect of the exciting current in varying the ratio of transformation would be almost the same as in varying the phase-angle. As a limiting value it is pretty safe to say that a transformer which would have one per cent. error at any point in ratio, would also have an angle between the primary and secondary current not greater but probably less than one whose sine or tangent is 0.01.

Suppose in an actual case the ratio of transformation in a certain transformer carrying a given load would be 1.02 (the ratio of ampere-turns must be used here as transformers usually have a few secondary turns omitted). The practical limits of the angle would be $\theta = \sin^{-1} 0.02$ = about one degree. Such an angle would cause an error due to phase-displacement of practically nothing at power-factor 1 and about 3% at power-factor 0.5.

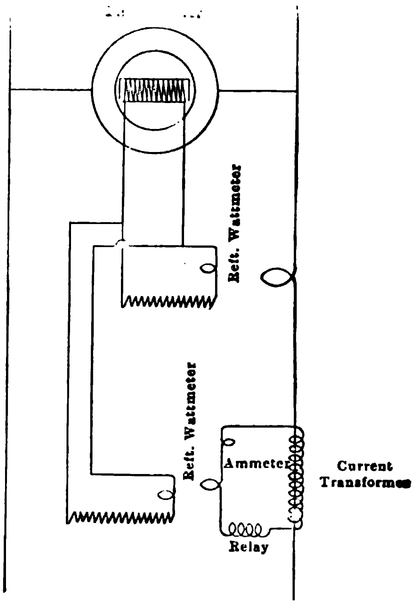

Fig. 8b.

The iron in these transformers is employed at a very low density. What iron will do at these low densities is not generally understood. The requirements are not necessarily met by iron having the best characteristics for ordinary transformers. Aside from anything which can be done in the way of designing these transformers, the problem comes down to a question of whether we can procure material having the necessary good qualities at the density used for the core. The value of the whole device depends on this core and it has been along this line we have been recently working to perfect the core as much as possible. As showing what can be accomplished in a transformer built of material procurable in sufficient quantities to make transformers commercially, your attention is directed to one of several transformers which were recently made to meet some special conditions (Fig. 10) in which, between one-tenth load and full load, the maximum difference in ratio is hardly more than one-half of one per cent., and between limits somewhat greater than this, the deviation has been limited to one per cent.

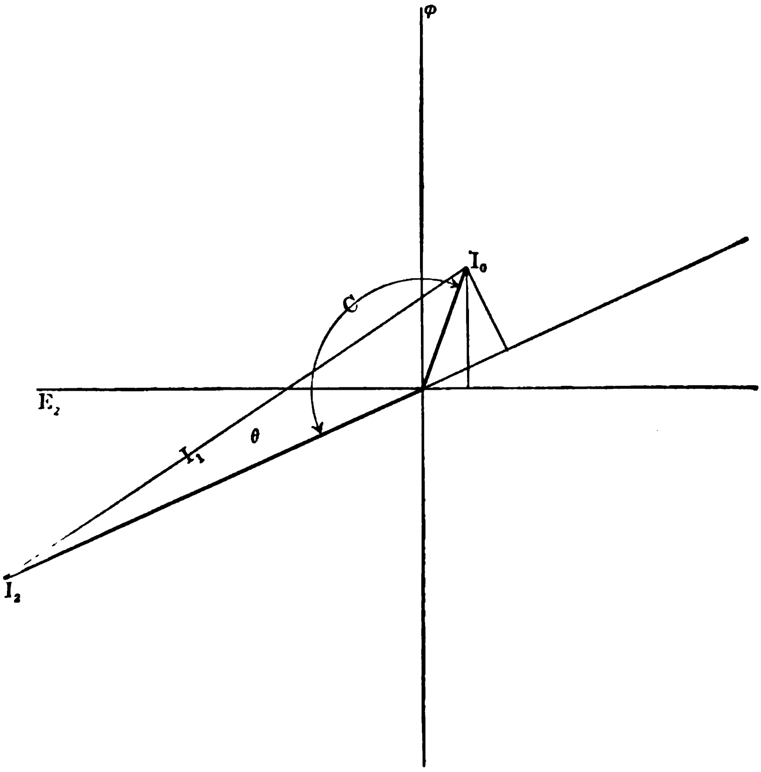

Fig. 9.

It is also apparent from the diagram of the author that it is possible, by properly arranging the power-factor of the secondary load, to bring the phase of the primary and secondary currents into actual coincidence. In many cases where very accurate work must be done with these transformers, that is, where the conditions of the test are such that a wattmeter cannot be directly applied, it is useful to understand this relation, and to control the power-factor of the secondary load so that the primary and secondary currents come in line.

When the power-factor of the secondary circuit, including that portion of it which is within the transformer, is equal to the power-factor of the core, the two currents, I_0 and I_2, are in line and the primary current I_1 is also in phase with the secondary current reversed.

When the power-factor of the secondary is higher than that of the core, (the usual condition) the secondary current leads the primary: and conversely when the power-factor of the secondary is lower than that of the core, the secondary current lags behind the primary. Such a condition is present at times when the secondary load on transformers is largely made up of a relay. It is on this account that the disturbing effect of comparatively large inductive loads on current transformers is minimized, the primary and secondary currents then being very nearly in phase, and, although the ratio error is then a maximum, the total error of a connected wattmeter is sometimes not greater than it would be if the relay were not included. By means of a knowledge of the various quantities involved, the combined circuits can be arranged to give the best results. In using current transformers for laboratory testing, it is possible to obtain very accurate results by computing current ratios from the exciting-current curve, and by means of connections, as in Fig. 8A or 8B, to adjust before each reading for 0 phase-angle between primary and secondary the ratios then become $\frac{I_2 + I_0}{I_2}$ directly, and the correction for phase-angle disappears. Again, if potential transformers are also used the proper phase-angle between primary and secondary currents in the current transformers can be produced to compensate for the small phase-angle in the potential transformer, thus allowing the true power to be directly determined from the instrument readings without correction for phase-displacement in either transformer.

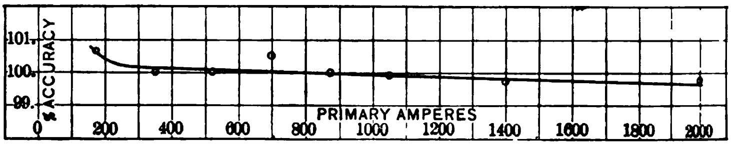

FIG. 10.—E-15 Current Transformer, No. 418561, Spec. 106262, Ratio 400 : 1, % Accuracy on 25 Cycles. Secondary Load: Portable indicating wattmeter an equivalent of 190 ft. leads of No. 10 B. & S. copper. Volt-amperes, 14.0. Power-factor, 0.85.

A paper presented at the 210th Meeting of the American Institute of Electrical Engineers, New York, October 26th, 1906.

THE AUDION.

A New Receiver for Wireless Telegraphy.

BY LEE DE FOREST.

The story of the development of a device of a distinctively new order, from its first inception to its practical reality, adds a human interest to its description which is perhaps too often lacking among scientific records.

In 1900 when I was beginning experiments on the electrolytic responder, it was my good fortune to have to work upon it at night in my own room, at a table beneath a solitary gas-burner with Welsbach mantle. My source of hertzian waves was the discharge of a small induction-coil placed in an opposite corner and set into operation by a key closed by pulling a string. One night I noticed to my surprise a decided diminution in the light from the incandescent mantle whenever the coil was sparking. The constant recurrence of this effect induced me to investigate. By proper adjustment of the inflow of gas and air to the burner, an almost complete extinction of its light was obtained during the sparking of the coil. Another adjustment even allowed an increase of the light above normal For several days I was elated over the tremendously sensitive and altogether novel type of hertzian-wave responder thus accidentally discovered. But alas for the over-sanguine spirits of the young investigator! When I thrust my induction coil into a closet and closed the wooden door, thus shutting off the sound of its vibrator and spark, my gas-light ceased to fluctuate.

I found I had merely discovered an extremely responsive form of the sensitive gas-flame, and that a bunch of jingling keys, or a smart clapping of the hands were almost as efficient generators of these hertzian waves as was my induction coil. To hopes unrealized this was indeed the " Light that Failed."

But the few days of illusion had set me thinking. Here in the flame around this incandescent mantle was matter in a most mobile, tenuous state, extremely sensitive to sound and heat vibrations, infinitely more delicate than any arrangement of solid or liquid particles. Why should it not then in some phase or fashion respond to the hertzian vibrations also?

Unable to dislodge this conviction from my mind, I began later to search for the genuine response to electric vibrations in the gas-flame. I found the conductivity of the incandescent mantle surprisingly small however for any voltages which would be practical in a wireless receiver.

By soaking the mantle in a potassium or sodium solution and drying, I was finally able to pass a small current from a dozen dry cells through the flame surrounding it, using two platinum electrodes with a telephone receiver in circuit, and get a faint response to the genuine hertzian wave. The discovery that the effect predicted was actually present was intensely gratifying.

Experiments followed with the bunsen-burner and other forms of flame. In the coal-gas flame the exterior luminous portion is positively electrified, the interior negatively. To render these flames sufficiently conducting, salts of the alkali metals were introduced. Of these the cæsium, potassium, and sodium salts are the most conducting, and in the order named. These salts were either injected into the flames as solution, or preferably put in a little platinum cup held in the luminous part of the flame and made the cathode of the telephone circuit.

A platinum wire or disk held about 2 mm. above this cup acted as anode. The antenna and earth connection, or the two terminals of the oscillating receiving circuit, were connected to these platinum electrodes. An electromotive force of 6 to 18 volts supplied by a battery of dry cells was sufficient to give a current of several milliamperes through the colored flame.

This early form of Audion, the flame receiver, was remarkably sensitive to weak high-frequency oscillations. The sound heard in the telephone was an exact reproduction of that of the transmitter spark, in pitch, variation of intensity, etc.

It was observed that the increase of current with electromotive force did not follow Ohm's law; a saturation value of the current was observed. Wilson has found that the maximum current which a salt vapor in a flame can carry is equal to

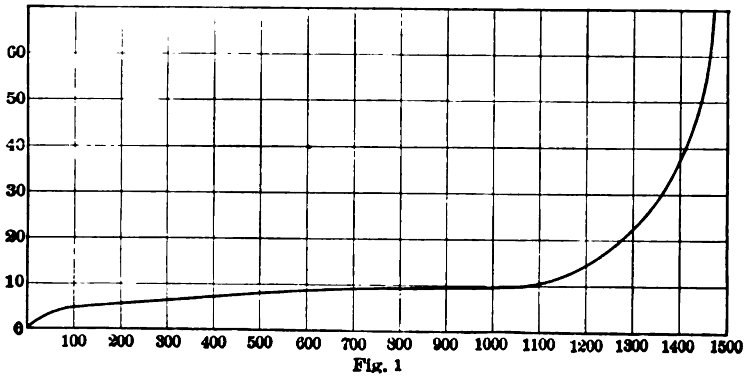

Fig. 1

the current which if passed through an aqueous solution of that salt would electrolyze the same quantity of the salt as was imparted during the same unit of time to the heated gas.

Beyond this saturation value the current will not rise until

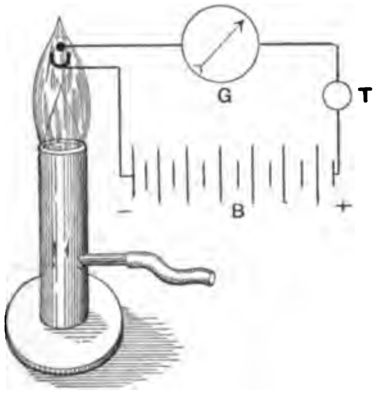

Fig. 2.

the electromotive force is great enough to enable the field itself to ionize the gas; that is, until the velocity imparted to the negative ions by the field is sufficient to enable them to separate the gas molecules with which they collide into positive and negative ions

The conduction through flames under the conditions I am describing is due chiefly to the negative ions generated, and these are chiefly in the vicinity of the metallic cathode. It is necessary that the alkali vapor comes in contact with the glowing metal. The increase of conductivity of a flame by the addition of a salt may amount to several hundred per cent., and is due, not to the presence of the metallic atoms in the flame itself, but to the increase in ionization produced by the salt at the electrodes, notably the cathode.

The velocity of the negative ions in flames at atmospheric pressure increases rapidly with the temperature. Thus at 2000° cent. their velocity is approximately 40 times that at 1000° cent. At 1000° cent. the ratio of velocity of negative ions to positive ions is calculated as $\frac{26}{7}$. At 2000° cent. this negative ion velocity in flames is about 1000 $\frac{\text{cm}}{\text{sec}}$ for a potential gradient of one volt per centimetre.

Now suppose the average velocity of a negative corpuscle to be proportional to the electric force; this velocity, for a potential drop of 10 volts between the electrodes as I use them, is of the order required to traverse the distance between the incandescent body and the platinum anode during the time of one half the wave period of the electrical oscillations ordinarily used in wireless telegraphy. I shall return later to the bearing which this fact has upon a suggested explanation of the effect of the hertzian oscillations upon the gas receiver.

On account of the ionization of the gas near the incandescent metal, and the greater velocity of the negative over the positive ions, it is to be expected that even if no external electromotive force be applied to the electrodes, and one of these be relatively cold, a current will pass along a wire connecting the two electrodes, whose direction is negatively from the hotter to the cooler body in the flame. In other words, the colder body will be the anode, positively charged.

Now if the hertzian oscillations traverse the hot gas, the momentary potentials thereby impressed upon the moving ions will conceivably interfere with their motions, or with the rates of recombination between the positive and negative ions, and thus affect the current flowing through the wire. A telephone connected between the electrodes indicates that changes of a surprising amount in the momentary potential difference, or flux, across the electrodes are effected by the high frequency oscillations, even when no external battery is applied.

When a battery of from 6 to 20 dry cells is connected across the two electrodes, the positive terminal to the cooler electrode, the potential current curve for the conductivity of the gas is at first approximately a straight oblique line, the current through the flame increasing with the electromotive force.

Soon, however, this proportionality of current and voltage ceases, and a stage of saturation is reached where there is no appreciable increase of current with increase of voltage. But when the potential difference is raised sufficiently to ionize the gas, a stage is reached where the current increase is far more rapid than that of potential difference. This last potential gradient depends upon the pressure of the gas; it is directly proportional to the pressure. This is given by Thomson as about 30,000 volts per cm. for atmospheric pressure; but with incandescent gases in an enclosed vessel at one mm. pressure a gradient of 40 volts per cm. is sometimes sufficient to produce this critical stage.

In the case of the flame the distances between the electrodes figures very little in the amount of current flowing, the potential drop, or the sensitiveness to hertzian oscillations, because most of the ionization at low voltages takes place at the electrodes.

The size and shape of the electrodes are of small moment. I prefer a trough cat anode 1 cm. long by 2 mm. wide, holding the potassium salt, as cathode, and a small platinum wire parallel thereto and held 2 to 10 mm. above it as anode.

The trough electrode should preferably be at the upper tip of the oxidizing flame at its junction with the reducing flame. When this is made negative the current is saturated with a comparatively small potential difference. The gas-burner itself may be used as one electrode. The flame must be steady and kept rich in salt. The current of up-rushing flame makes a rumbling noise in the telephone, which may interfere with the detection of faint signals. This disturbing sound increases with too great applied potentials.

The temperature, especially of the electrodes, is an important factor. At red heat these give off positive corpuscles; at white heat both positive and negative appear, the latter predominating. The electrode containing the salt should always be incandescent, so that the excess of negative ions given off and streaming towards the other electrode will increase, rather than diminish, the current due to the flame itself. The extreme sensitiveness of the flame when ionized to thermal variations is illustrated by the fact that a distinct response is heard in the telephone receiver when the mere tip of a cold pin is suddenly introduced into the flame. The sudden introduction of a cold body into the active part of the flame always reduces the response. The salt is best placed in, or on, one of the electrodes rather than held in the flame in an independent receptacle, or injected into the gas.

The applied electromotive force is a determining factor in the sensitiveness of this receiver. The response seems greatest where the potential current curve is passing from the oblique to the horizontal portion, where the saturation value is about to be reached Under these conditions the sensitiveness of the flame Audion is of the same order as that of the electrolytic receiver using a glass-jacketed electrode. The flame is not most sensitive when the flux is greatest. There is a close relation between the degree of heat and the critical impressed voltage

Considerable difficulty was found in getting an absolutely steady flame, even when protected by a chimney, as the slightest air current will deflect the sensitive portion from the electrodes, altering the sensitiveness of response

I next sought the phenomenon in the hot conducting gases of the electric arc. If a wire be connected to the positive carbon of the arc and led through a telephone to a third electrode, platinum or carbon, which is inserted into the border of the arc, a considerable current passes through the telephone. If these two electrodes are now connected to the terminals of the receiving oscillating circuit, the conduction of the leak current across the gas to the third electrode is sensibly affected by the arriving hertzian oscillations, if sufficiently intense. A local battery can also be inserted in series with the telephone, but the voltage drop across the arc is usually too great to require this.

Even when the arc is fed from a storage-battery, and cored carbons used, the hissing and frying noises in the telephone (probably due to the oxidation of the terminal by the air) are generally too troublesome to allow a clear reading of weak signals with this form of Audion.

The principles involved in its operation are much the same as for the flame Audion. And although the intense ionization produced by the heat of the arc renders it extremely sensitive to slight local variations, its practical requirements make it less available as a wireless receiver.

Inasmuch as the gases ionize more readily at lower heats and are in their most mobile, delicate, and sensitive conditions in vacuum, it seemed to me certain after experiments with the flame that the attenuated and ionized gases around an incandescent filament would undergo very considerable changes when subjected to hertzian oscillations.

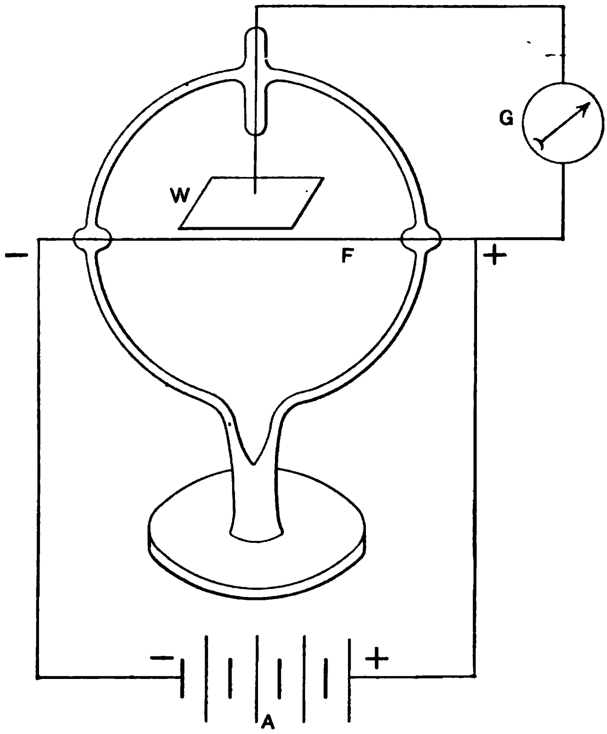

Fig. 3

Elster and Geitel,* beginning in 1882 a systematic investigation of the ionization produced by incandescent metals, frequently employed an exhausted glass vessel containing an

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*Elster and Geitel, Wied. Ann., xvi., 1882.

insulated platinum plate, stretched close to which passed a fine metallic filament brought to incandescence by an electric current. Fig. 3.

Ordinarily at atmospheric pressures and red heats a positive charge was produced upon the plate, of the order of a few volts. This potential increases until the wire is at a yellow heat. As the wire gets hotter the potential decreases, until at a bright white heat the potential of the plate is very slight. Diminishing air pressure has but slight effect upon the plate potential until very high exhaustions are reached, when this potential begins to diminish and may even change sign, and as the exhaustion proceeds may reach a very large negative value. This pressure where the plate charge changes sign depends upon the temperature of the filament, being higher at higher temperatures.

Long-continued heating and expulsion of gas from the incandescent metal play a considerable part in the electrical phenomena. Long-continued incandescence favors the negative electrification of the plate. The presence of oxygen aids in the carrying off of a negative charge, thus producing negative electrification around the wire; hence the action of oxide of metal on filaments tends to increase the discharge of negative electricity. But oxygen also hastens the disintegration of the filament.

Gases which are dissociated by heat conduct on quite a different scale from those like air, hydrogen, or nitrogen. Examples of such are the vapors of iodine, bromine, chlorine, potassium, iodine, etc. These furnish a much larger supply of ions than the others. This dissociation occurs chiefly where the gas is in contact with the glowing electrodes. Of the metals, sodium and potassium have the highest conductivity under the above conditions, for the emission of negatively electrified corpuscles from sodium atoms occurs even at low temperatures; and I have used carbon filaments coated with a potassium compound. The conductivity of cold mercury vapor does not seem greater than that of air.

With hydrogen the plate becomes negatively electrified even at atmospheric pressure; and when the filament is carbon instead of platinum the electrification on the plate is always negative. This means that the gas will discharge the plate if positively electrified; that is, a positive current will pass from the plate to the filament in the gas.

The electrification produced in the neighborhood of an incandescent wire is a complicated effect; it depends on the temperature and nature of the filament, and on the nature and pressure of the gas. It furthermore depends upon the electric and magnetic forces to which the vessel is subjected; and I have found that the shape and area of the plate or plates, the condition of its surface and edges, as well as its distance from the filament, are very important factors.

If the metal plate be connected by an outside wire to the positive terminal of the hot filament, a leak-current from the plate to the filament through the gas will be set up, as Elster and Geitel first found, passing mainly to that portion of the filament near its negative terminal. If the resistance of the lamp filament and the lamp's voltage be high, a very considerable leak current may thus be set up.

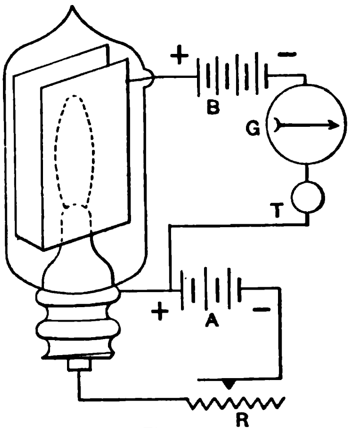

Fig. 4

In Fig. 3 a battery of from 3 to 18 dry cells is connected between the positive end of the filament and the platinum plate W, the latter being connected to the positive pole. The saturation current increases rapidly with the heating current through the filament, which also increases the velocity of the negative ions, as does also an increase in the applied electromotive force between plate and filament.

The rate of discharge of negative electricity from glowing carbon greatly exceeds that from platinum, while that from tantalum and other of the newer filaments, given the same heating current, surpasses the rate of discharge from carbon.

Thomson states the equation connecting the saturation current with the temperature as

$$\left(I = A\,\theta^{\frac{1}{2}}\,e^{-\frac{b}{\theta}}\right)$$

where θ is the absolute temperature, a and b are constants.

At 2000° cent. this rate of emission from a platinum wire in high vacuo amounts to 0.1 ampere per sq. cm. of hot surface. For carbon this current can equal several amperes per sq. cm. surface. In the Audion the flux current ordinarily ranges from 1 to 5 milliamperes.

The metal dust, or even vapor from the incandescent filament may play a part in the phenomena but not a controlling one. Thomson has shown that the value of e/m for the carriers of electricity in the type of exhausted vessel described is the same as its value for the carriers of the negative electricity in the cathode rays, or in the discharge of negative electricity from metals illuminated by ultra-violet light. In fact in many ways the behavior of the Audion, notwithstanding the extremely low potentials used, is very similar to that of a cathode-ray tube; and in one or two small pea-lamps where the anode disk was close to the bend of the filament I have actually obtained, at only 22 volts, a blue-white beam of light playing between the filament cathode and the anode. Upon the approach of a powerful magnet this beam could be concentrated and deflected. A great increase in the current through the telephone marked the formation of this beam, and a violent hissing or squealing sound began when the magnet was approached.

The corpuscles at the filament are attracted by the metal of the filament, and to escape into the surrounding space they must be given sufficient kinetic energy to carry them through the surface layer where this attraction for the carriers is appreciable. Thus as the temperature of the filament increases, a larger number of the carriers can escape from the wire. But the saturation values of the flux current do not depend upon the velocity of the ions, but only upon the number of ions produced in unit time at the surface of the hot metal.

The source of ionization is confined to the gas immediately surrounding the filament. The velocity of the ion at any instant is dependent on its distance from the filament, because the temperature is not uniform between filament and plate. The ratio of the velocities of negative to positive ions varies greatly with the temperature. This is given as 1000 to 62 at 2000° cent.

This fact explains why the positive conductivity of the gas in the vessel is almost entirely from the cold to the hot electrode in the gas, and not in the reverse direction; and why this unidirectional quality is more marked for higher temperatures of the cathode, the anode being kept cold.

In the form of Audion illustrated in Fig. 4, I employ two platinum wings parallel to the plane of the bowed filament and about 2 mm. on either side of it. These wings are soon coated with an iridescent deposit from the metal filament, especially at the portions opposite to the negative half of the filament. They become quite hot at this short distance, but not sufficiently hot to take part in the ionization of the gas.

When connected in the oscillation circuit as shown, properly attuned to the receiving electromagnetic impulse from the antenna, the Audion, under proper adjustment of heating current and battery *B* potential, is extremely sensitive, giving response in the receiving telephone several times as loud as any other form of wireless receiver when subjected to the same impulses. It is, however, less sensitive to atmospheric or static disturbances, which are strongly damped or a-periodic.

I find the device extremely closely tuned with the syntonizer, for its operation seems to be dependent upon the sum total of the energy received from the complete wave-train rather than upon the maximum first impulse of the train. In other words, while instantaneous as far as our senses or instruments can perceive, its action is sufficiently sluggish to be determined by the additive effect of the entire received electroradiant energy through a short time-interval.

When the filament is first lighted, an appreciable interval, about one-quarter second, elapses before the full sensitiveness is established. Before the flux reaches a steady state there is a period during which the number of ions is steadily increasing. As result of the colliding of the initial ions with the gas molecules the number of ions and the current rapidly increase, until an equilibrium is finally attained.

The Audion, to a greater extent than any other responder, is self-tuned. I mean that by regulating the heating current, the potential between wing and filament, or the distance between these, the Audion can be made to a great extent selective *per se* to certain received impulses. And the determining factor here is not merely the frequency of the electrical oscillation; the spark frequency, or factors determining the total amount of energy received during a very brief unit of time, determine to an extent the amount of its response. Thus with 12 volts across it, it may give a loud response to a transmitter *A*; and with 10 volts " bring in " another transmitter *B* to the almost complete exclusion of *A*, although *A* and *B* are of equal power and of approximately the same wave-length, but differing considerably in spark frequency. Similar discrimination can be produced by adjustments of the heat of the filament, which also governs the amount of flux through the gas.

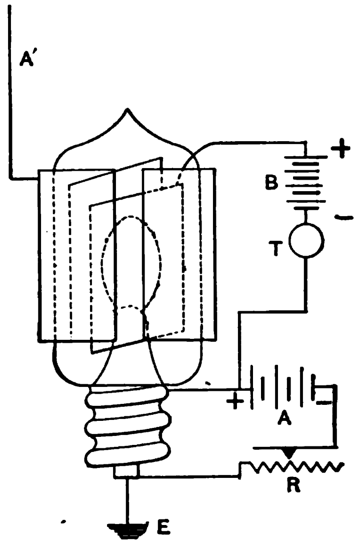

Fig. 6

This flux is generally reduced when the Audion is placed in a strong magnetic field, especially when the lines of force pass through the gas parallel to the plane of the wings, at right angles to the electric field. By this means also a tuning can be effected.

Again it is not necessary to connect the anode to a terminal of the oscillating circuit. One terminal may be attached to a metal sheath or ring surrounding the glass vessel, thus forming a condenser with the filament or the conducting gas within the tube. In this case the adjustment of the syntonizer is generally different from that required for the same oscillation frequency, when the interior wing is directly connected in the oscillation circuit. In this condenser arrangement also the sound heard in the telephone changes its quality to an extraordinary degree, being of a dull muffled nature rather than sharp and staccato. Signals of this quality are sometimes much more readily distinguished from the " static " disturbances which so frequently render wireless signals difficult to read. The operator has thus a ready means of changing the quality of the received signals to suit the conditions. This latter type of Audion is the one I have found most serviceable in practice.

The Audion may even be placed in the space between two

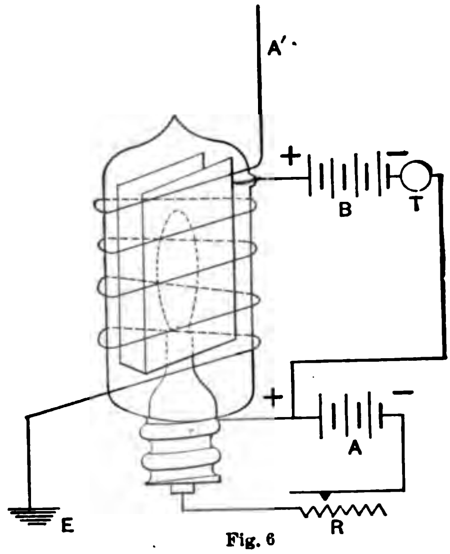

Fig. 6

plates of an air condenser in the oscillating circuit. A flat-walled type of tube is preferred for this arrangement. Again the electrical oscillation may be led through a coil of wire wound round the outside of the tube (Fig. 6), and not through the Audion at all, or through a flat coil brought up close to the tube, with its axis perpendicular to the filament. In this arrangement it is chiefly the electromagnetic component of the passing oscillation which affects the motion of the ions within the vessel. The ions are readily influenced by a magnetic field.

By shifting the syntonizer connections from the wings to this helix, I have been able to cut out completely signals from a transmitting station so near as to baffle all attempts with the ordinary tuner methods, and to bring in other relatively faint signals.

The Audion has the further advantage of entire absence of adjustment in the receiver itself. It gives no evidence of fatigue under any conditions of use. Furthermore, it requires no protection from the violent impulses of the transmitter at its own station, whereas the sensitiveness of the electrolytic receiver is completely destroyed by one such violent impulse, unless its small electrode is protected by a shunting switch.

I have arrived as yet at no completely satisfactory theory as to the exact means by which the high-frequency oscillations affect so markedly the behavior of an ionized gas. Fleming points out that when the cold plate of the Elster-Geitel tube is connected to the positive end of the filament, and the two put in a high-frequency oscillation circuit, only the positive half of the oscillation can pass from the plate to the filament across the gas. He uses this principle to rectify the hertzian oscillations, and applies the unidirectional currents of the oscillations themselves to operate a sensitive galvanometer, or direct-current instrument, for quantitative measurements over short distances.

When an independent external source of electromotive force is applied, in the manner I have described, the action becomes quite different. It then operates as a *relay* to the hertzian energy instead of merely rectifying this energy so that it can be used directly to give the sense signal.

The Audion therefore is tremendously more sensitive and available in practical wireless. A sensitive direct-current instrument in the *B* circuit shows a steady deflection varying not a whit, by increase or decrease, during the reception of strong "wireless" signals. An electrolytic receiver or "polariphone" under similar conditions would cause a great deviation in the deflection of a milliammeter, although the signals in the telephone with the electrolytic are not so loud as with the Audion.

I have connected two Audions in series in opposition in the oscillating circuit, each with its separate heating circuit, and still heard the signals in the telephone connected to the second Audion equally well whether the wing in the first be connected to the wing or to the filament of the second.

When one of the tubes is unlighted, no high-frequency impulses pass through it unless the wing and filament are very close together. When cold it acts merely as a condenser whose armatures are the wings and filament and whose capacity is extremely small.

I have laid considerable stress upon the potential gradient or " variation " layers which exist near the surface of the electrodes when the external applied electromotive force is considerable, for the reason that their existence seems to play a very important rôle in the response of the Audion to minute high-frequency oscillations.

If the velocity of negative ions is very large compared to that of the positive ions, the curve representing the distribution of electrical intensity between the two electrodes is represented by the following, which is typical.

When ions of both signs are present in the gas and when the electric field is so strong that most of the positive ions are driven from the anode and the negative ions from the cathode (the filament), we will have an excess of cations in front of the anode and of anions surrounding the cathode. It is seen that the variation in potential lies chiefly in the thin layers of gas in front of the two electrodes. It is convenient to speak of these regions as the " variation " layers.

As Thomson points out, in passing from the inside to the outside of the layer of ionized gas we have to pass across a layer of electricity. This will produce a discontinuity in the electrical intensity equal to 4 π times the surface density of the electrification. There may thus be a great difference between the electric intensity inside the layer and that just outside. The potential drop across the layer is proportional to the square of the current; the falls of potential at the positive and negative electrodes are proportional to the squares of velocities of the positive and negative ions; and the velocity of the ions is proportional to the electric force acting upon them.

These variation layers at the electrodes of the Audion are analogous to those in the cathode-ray tube. In the cathode tube a sudden drop in potential called the " anode fall of potential " occurs quite close to the anode; and in the layer called the Crookes dark space, or cathode dark space, there is a still greater fall in negative potential. But the voltages here are enormously higher than those in the Audion. As the gas pressure in the cathode tube diminishes, the dark layer, or the cathode drop layer, becomes broader. $D = \alpha + \beta\lambda$; that is, the width of the dark space is proportional to the mean free path of the molecules, beyond a certain distance α in front of the cathode. Schuster found that the thickness of the cathode drop layer increased slightly with the current passing through the gas; but Wehnelt found just the reverse. Both may be correct on different sides of some particular value of the current for which the width of this space is a minimum. This is interesting in view of the fact that there is a certain current flux across the gas of the Audion for which the response of the hertzian oscillations is maximum; supposing this response is maximum when the width of the variation layer around the filament is minimum.

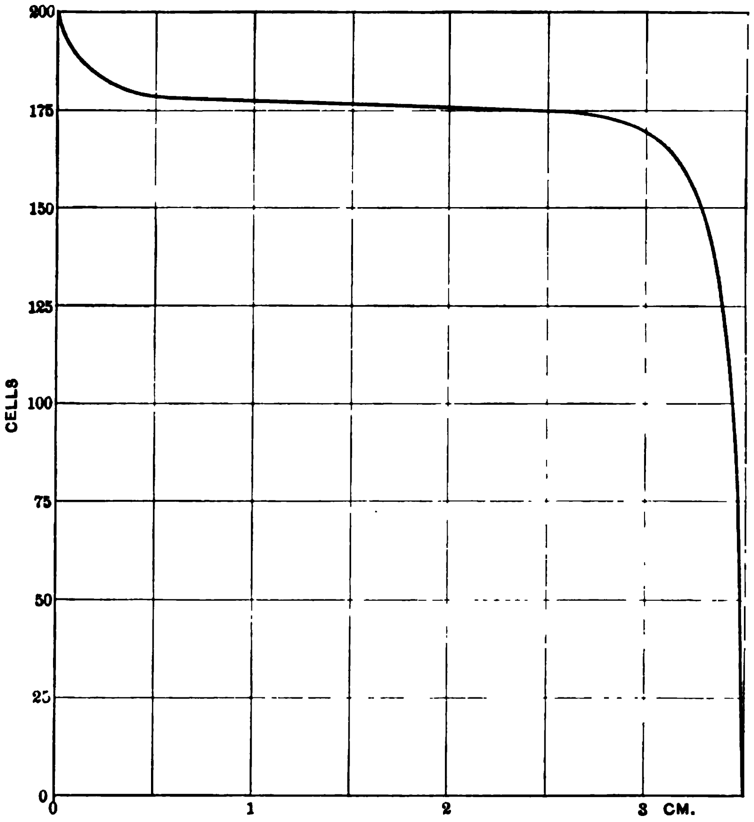

Fig. 7

Within the cathode layer there exist only negative ions, these being shot off from the cathode. Right outside of this, in the region called the "cathode glow," ionization of the gas from collisions with these negative ions begins, and the width of the cathode dark space is about the range of the " mean free path " of the ions.

If a similar state of affairs exists around the filament of the Audion, and if this mean free path of the cations coincides with the excursion of the corpuscles during one half the oscillation period of the impressed hertzian vibration, we might expect under these conditions a maximum effect of response to oscillation of the particular wave-frequency. Or a similar effect might be expected if the excursion in question is that of an ion from the cathode across the gas up to the layer surrounding the anode.

The extent to which the sensitiveness of the Audion is sometimes governed by a very slight change in the heating current, or in the potential drop across it, seems to lend plausibility to such an explanation. And it has been shown that in conducting flames at atmospheric pressure a negative ion acting under a potential gradient of 10 volts per mm. would travel approximately 1 mm., or a commonly found distance between the electrodes in the Audion, in $\frac{1}{1,030,000}$ part of a second, which time-interval is of the order of one-half the wave period of some of the longer oscillations used in wireless telegraphy. For reduced gas pressures the natural excursion of the ion would be more rapidly accomplished, but its velocity can be governed within wide limits by regulating the applied electromotive force. When we send more current through the filament we increase the potential difference between filament and anode as well as increase the heat. Both changes act to increase the ionic velocity.

In Humstedt's experiments, where a cathode-ray tube was exposed to high-frequency oscillations, the width of the cathode drop layer, or dark space, diminished as the frequency of the oscillations increased; as if there might be some connection between the period and the time involved in the immigration across. And many facts observed in connection with the Audion, otherwise difficult to explain, tempt one to suppose that here the degree of response is connected with the relation between the product of velocity of the ions by the distance between the electrodes, and the period or half period of the electrical oscillations received.

When the anode consists of two parallel plates instead of a cylinder, there will be a maximum of positive electric density along their vertical edges. The more intense parts of the electric field will involve the larger number of ions, and on the anode these will generally be located at the vertical edges of the parallel plates, provided these are not too far from the filament.

With this type of anode a peculiar and sudden inflection point in the current-flux diagram, as the heating current is gradually increased or decreased, is noticed. The flux goes on increasing, then suddenly drops back to a lesser value; at the same time a click is heard in the telephone in the *B* circuit. Then as the heating current is still further increased, the *B* flux is again increased. These same cusp-points in the curve are obtained if the *A* circuit be kept constant and the *B* voltage is increased instead.

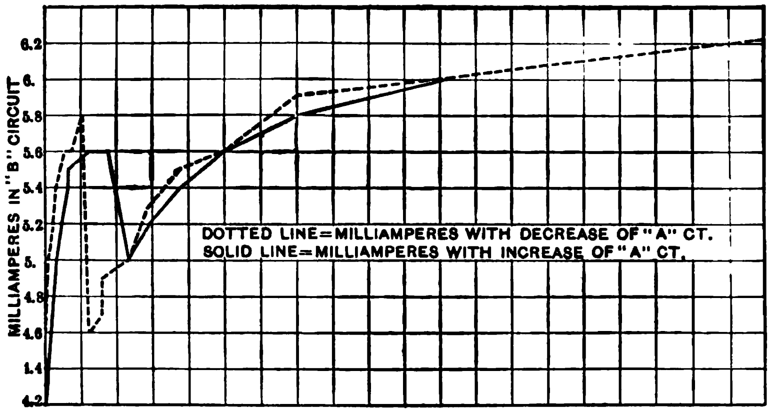

Fig. 8

Similarly a click is heard when the flux current is being reduced from a higher value, only the location of the cusp on the curve of decreasing current is not coincident with but lags behind that observed when *B* is being increased. This second cusp-point shows a sudden *increase* in the flux current, when the critical point is reached, to a value previously passed through. Naturally the sharpness of these cusp-points can be smoothed out or quite obliterated by putting impedance in the *B* circuit in series with the telephone.

The diagram (Fig. 8) shows the relative magnitude of these sudden alterations in the flux current obtained with a certain sample Audion, and Fig. 9 the decided hysteresis effect, showing how the actual B current lags behind the increasing or decreasing electric field which produces it. This hysteresis effect

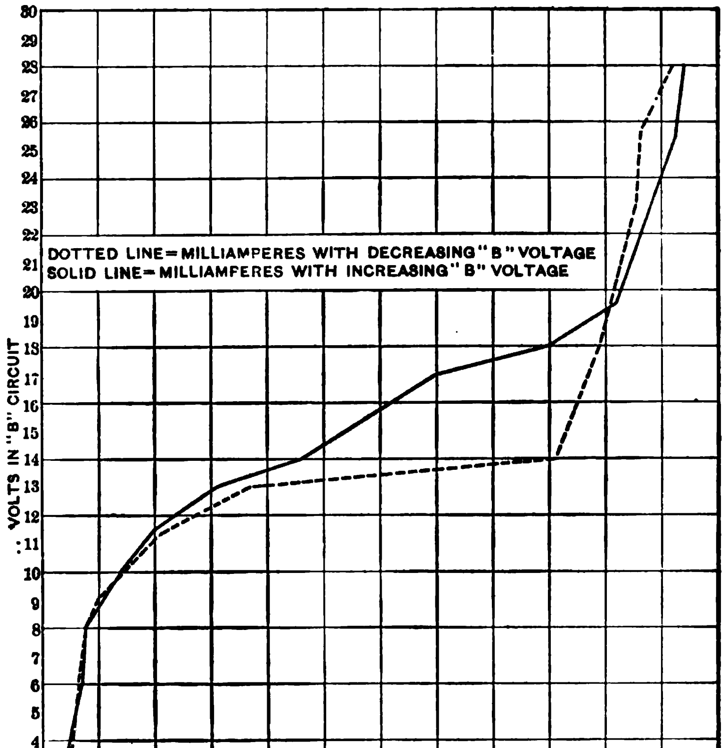

Fig 9

is very like that obtained when the molecular structure of iron is altered under a changing magnetic field. Doubtless it is here due to a reluctance of the ions to accommodate their paths and velocities to the impelling electric forces. The area included between the two curves represents the work lost in accomplishing tnis conformation.

These hysteresis curves are always obtained, even though the anode is in the form of a cylinder or flattened cylinder without the vertical edges; but the *reactive* cusp-points in the curves are never obtained save with the plane anodes.

Zeleny* has found a similar very curious hysteresis effect in the currents obtained from the ions from a platinum wire when heated and exposed to ultraviolet light. When the metal was cooling, these currents were greater than those for the same temperature when the metal was being heated. In this case, heating the wire produces some change in its surface, possibly in the amount of gas condensed thereon or absorbed by it, from which it recovers very slowly.

As *B* voltage is increasing and *A* current is increased and decreased, I find that the points at which the cusps occur on the increase and decrease *A*-*B* curves coincide more and more nearly, and at the same time these cusps become less and less violent. The hysteresis effect when the heating current is increased and decreased is less pronounced as the *B* voltage is increased. As shown in the curves for a large *B* flux, the two *A*-*B* curves for increasing and decreasing *A* current coincide almost exactly until *B* flux is reduced to a certain amount. They may again cross each other at a lower point of *B* flux, again diverge, and then coincide once more near their origin. These curves were all taken with Audions of the double-wing type, which feature may account for some of the very peculiar characteristics observed.

The filament is always at some part nearer to one wing than to the other. Hence the *B* flux is chiefly concentrated on this wing or portion of wing, like a beam of cathode rays. We may suppose that as the *B* voltage is increased, as when more heating current is passed through the filament, the flux is increased and spreads out over this wing until a new sheaf or " ray " of ions, starting off from the filament from another part or in a new direction, suddenly leaves that wing and takes by preference a shorter path to the opposite wing. We would suppose that a new path thus taken would first be located on one of the vertical edges of the wings parallel to the filament.

This sudden diminishing of the intensity or density of the original beam of ions may be accompanied by a decrease in the velocity of propagation of the ions, and thus the resultant flux

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*Zeleny, Physical Review, Vol. XII, 1901.

be actually less than before. The reverse operation will occur when the *B* flux is being decreased from a high value.

When the anode consists of one wing only, no such reverse cusp-points, or reversals of the flux increment, have been obtained. With a single-plane anode, however, there is found a point at which the flux, if increasing, assumes a sudden increase in magnitude, representing an abrupt rise in the otherwise smooth flux-voltage curve; and the reverse when the current flux is being decreased.

These effects seem to relate to the increased values of the positive variation layers along the vertical edges of the anode which parallel the filament. The distribution of the charge upon the surface of the plate may be described as analogous to that of a thin film of liquid which coalesces and is heaped up along the edges, and from which, when the liquid is by any means drawn away, there is a sudden recession; the liquid, on account of the surface tension, letting go or taking hold of the edge all at once.

It is significant that just at a cusp-point the sensitiveness of the Audion to the hertzian oscillations attains a marked maximum. Under the critical conditions then obtaining, the slightest change in the applied electromotive force is accompanied by relatively great changes in the *B* flux.

In framing any theory of the action of electric oscillations in the Audion a variety of complex, contradictory phenomena are met with, exceedingly puzzling to explain. An example is the fact that a continuous-current instrument in either the *A* or the *B* circuit shows absolutely no change of deflection, either of increase or decrease, when *B* is large and the Audion in its most sensitive condition. If only the positive halves of the oscillations pass from anode to filament these should increase the reading of a milliammeter in the *B* circuit during the passage of a long series of wave-trains of sufficient intensity. Or else the negative halves of these oscillations might be expected to diminish to a greater degree the positive charge on the anode, and result in a diminution of the *B* circuit. Or if both of these acted equally and oppositely no signal would be obtained at all, for the telephone diaphragm is utterly incapable of following such rapid increase and decrease in the *B* current, even if its impedance would allow these pulsations to pass through the circuit. Neither would the ear detect such vibrations.

If on the other hand the integrated effect of a complete hertzian wave-train were either to increase or decrease the B flux, a long succession of such effects, all of which must be of the same sign, ought to cause a change in the needle's deflection, as when a long Morse dash is sent out from the transmitting station. We have no reason to suppose that one wave-train, the result of one spark, would produce a momentary decrease in the B flux, indicated by a click in the telephone, and that the next succeeding wave-train from the next spark would cause an opposite *increase* in the B flux, and another similar click in the telephone. Such action would of course explain why a loud sound in the telephone might not be accompanied by any change in the sluggish ammeter reading, similar to the case of the magnetic detector.

The following explanation of the phenomena which seems to account for many of the peculiarities of this paradox has been suggested. It should be remembered that if the negative half of the electric oscillation can not pass through the gas from cold anode to the filament, the Audion electrodes during that half-period will act merely as the two armatures of a condenser. Even when close together, their mutual capacity, when the gas is cold, is exceedingly small, and only a very small positive charge can be held bound on the filament; or if there are sufficient free positive ions in the hot gap, the complementary positive charge will be held just on the outside of the " variation layer " at the anode.

The falls of potential across the variation layers at anode and cathode are proportonial to the squares of the velocities of the positive and negative ions; and the ionic velocities are proportional to the electric forces acting upon them. Supposing, then, that during the positive half of the electric oscillations the velocity of the positive ions is increased at the anode layer, and during the other half period the velocity of the negative ions is increased, due to the changes in the electric force acting upon them, then, regardless of the sign of the change of the velocities, the potential drop across the variation layers (which varies with the square of these changes) will be increased during the entire passage of the oscillation train.

The layer will act during this interval like a condenser, the potential drop across which is momentarily increased, which momentary increase will disappear with the passage of the wave-train. It will be as if the plates of a charged air condenser were suddenly further separated and then brought suddenly back to their normal positions; or as if the specific inductive capacity of the dielectric were decreased and then increased. This operation being repeated for every spark at the transmitter, a listener in the telephone in the *B* circuit will hear a sound whose pitch is exactly that of the spark, while a milliammeter in that circuit will show no variation in its deflection.

As the fall of potential across the variation layers is proportional to the square of the current passing, and to that of the impelling electric force, it is readily understood how, by regulating the heating current and the *B* voltage, an optimum value of the electrode drop may be obtained for which the effect from any given received impulses will be a maximum. Also, how by varying the distance between the electrodes the sensitiveness of response may be regulated.

Thomson states that the current between two plates for a given difference of potential varies inversely as the cube of the distance between the plates, up to the saturation-current stage. But in the case of the Audion, where the cathode is an incandescent filament, the law seems to be quite different. Thus for two anodes of equal area, one approximately four times as far from the filament as the other, the two currents were as 21 to 8. The flux here varies more nearly as the inverse distance.

The potential difference required to produce saturation is proportional to the square of the distance between plates and to the square root of the intensity of ionization. This latter depends on the temperature of the filament.

In the case of the parallel plates, only one of which is incandescent, or if both are heated but below yellow heat so that only ions of one sign (positive) are present and carrying the current, then this current as Thomson shows is:

$$i = \frac{9\,R\,V^2}{32\,\pi\,d^3}$$

where *R* is the velocity of the ion under unit electric force, *V* the potential difference, *d* the distance between the two plates. According to this formula the current varies inversely as the cube of this distance. But this formula will hold only when *R* is independent of *X*, which it will not be when the temperature through the space is not uniform. It holds also only for currents that are small compared with their saturation values; for the saturation currents depend not upon the velocity of the ions but upon the number of ions produced in unit time at the surface of the hot electrode.

But in the case of the Audion with small potentials, the closer the electrodes are together the more rapidly will the *B* current increase as the potential drop is increased. The trajectories of the ion are shorter and they therefore undergo fewer collisions, reunions, and retardations when the electrodes are close together.

In an Audion where the anode is far from the filament, the saturation current is not attained with the *B* voltages used in practice. We sometimes have instead its inverse counterpart, a saturation voltage, so to speak. As shown in the curve, at potentials from 10 to 18 volts a slight potential increment is accompanied by a very large increase in flux. And within these limits the sensitiveness of electric oscillations may be a maximum. The cusp-points, when present, are generally found near these points of inflection in the flux-voltage curves.

In some cases a remarkable lag or " creeping effect " is observed at this saturation stage. In one instance, the milliammeter needle crept slowly up, after *B* was raised to 14 cells, from 18 to 26 divisions. The current flux required something like 15 seconds in this instance to attain its full value. The filament in this case may have been undergoing some change which caused it slowly to discharge more and more corpuscles until that stage was reached where the recombination of oppositely charged ions in the gas exactly equalled the output of negatively charged ones from the incandescent surface. Sometimes this creeping is accompanied by a loud frying sound in the telephone.

MAGNETIC EFFECTS.

Thomson shows that at low gas pressures and high ionic velocities the ions, when placed in a strong magnetic field, will travel along the lines of strong magnetic force; but when the product of velocity and field is small the ion moves parallel to the electric force. If both magnetic and electric forces are uniform, the ions, both positive and negative, will move in the same direction and perpendicular to both *E* and *H*. When the electric field is not uniform but radiates from a point, and the magnetic field is uniform, the ion will describe a spiral traced on a cone of revolution whose axis is parallel to the magnetic field.

If the direction of E and H coincide the path of the ion itself is a helix of gradually increasing pitch, with its axis parallel to the lines of magnetic force. The radii of the spirals will be small compared to the length of the mean free path of the ions. This is especially true for the negative ions, even when the motion of the positive ions is but little affected by the magnetic field.

When the lines of magnetic force are perpendicular to the discharge in the cathode-ray tube, the magnetic field at all pressures retards the discharge and diminishes to a considerable degree the great drop in the electric force which occurs in the negative glow.

In general, it can be assumed that in a strong magnetic field the ions tend to follow the lines of magnetic force. The smaller the velocity of projection the more nearly does the path of the ion coincide with a line of magnetic force. In cathode-ray tubes the boundary of the negative flow may coincide with the lines of magnetic force.

In the case of the Audion, if the lines of a strong magnetic field pass through the gas parallel to the plane of the anodes, a marked reduction in the flux is obtained, sometimes amounting to 20 per cent. This effect is greater when the south pole of the magnet is nearest that leg of the filament which is attached to the negative terminal of battery A. The negative charge on this leg is of course greater than on the other, for the negative charge on the other is the resultant of the negative potential of battery B and the positive potential of battery A. And when the lines of magnetic force are so directed as to tend to sweep some of the negative ions off from the parts of the anode nearest to the filament leg which carries the greater negative potential, the reduction of the flux across the gas will be the greatest possible. Hence the magnetic polarity observed.

If the filament extend above the top of the anode, say for 0.5 cm., then a magnetic field parallel to the filament legs may tend to force certain lost ions into a downward trajectory so that they will strike upon the anode instead of passing off above it. In this case only is an increase in the B flux observed as a magnet is brought up to the Audion.

In general the flux will be diminished by the magnetic field. When the magnetic lines pass perpendicular to the plane of the wings the negative ions which are traveling in the direction of the magnetic force, from filament to wing, will be accelerated, but those originally traveling out from the filament in the opposite direction will be bent around or deflected from their direct paths; so the resultant will be a decrease of the total current flux.

When the field is intense, a marked frying or hissing sound in the telephone is heard, especially with the two-wing anode, and when the magnetic force is parallel to their plane and thus affects mostly the ions which are streaming towards their vertical edges. In the hissing arc parts of the arc are in rapid motion in the unstable portion around the edges of the positive terminal. Possibly also the presence of oxygen in the gas enters into the phenomena here as it does in those of the hissing arc. As the magnetic field lengthens the arc so here it lengthens the paths of the ionic discharge.

The hissing is much more violent when the surfaces of the anode instead of being plane are punched full of little holes whose ragged and protruding edges offer greatly increased opportunity for the ions to travel irregularly under the combined forces of the magnetism and of the electric charges heaped up at all such points and edges. In this particular Audion, I could get a great range of singing or squeaking sounds as the heating current was varied. Where the velocity of the ions is a maximum their deflections by the magnetic field will be lessened.

If the *B* flux is too great to give maximum sensitiveness of response, bringing up a magnet to the Audion will increase the strength of the wireless signals, because of the reduction of the *B* flux. Or if this flux be already below the optimum, then the presence of the magnet may decrease the sensitiveness. This effect may be more pronounced for one wave-frequency than another, in which case the Audion can be attuned by regulating the magnetic field to which it is subjected.

Consider the case where the electric oscillations instead of being introduced into the Audion through its interior anode are brought up to a metal plate outside a vessel. Electric displacement currents instead of conduction currents must then act upon the ions within the vessel and on the charges upon the electrodes.

Now in the case of an electromagnetic wave, where H and E are perpendicular to each other and to the direction of propagation, Thomson shows that if the product of $H \cdot \times e$ is large

(e being the electric charge on a carrier) the average velocity of the ion parallel to the direction of E is zero, and the wave will carry the ion along with it. When however $H \times e$ is small (no external magnetic field) the effect of the hertzian wave will be to superimpose on the undisturbed motion of the ion a small vibratory motion parallel to the electric force in the wave, and thus perpendicular to its direction of propagation.

A very convenient form of Audion for investigating the relations which the distance, area, etc., of the electrodes bear to its response is had by using a pool of mercury for the anode. This is conveniently held in one or more pockets blown in the walls of the glass vessel, and the filament so placed as to pass closer to some than to others.

Quite frequently I obtain with this arrangement two maxima of sensitiveness to the same transmitter, the filament-heating current remaining unchanged; thus one maximum for $B = 12$ volts, and a second for $B = 18$ volts. Again the sensitiveness is maximum when the mercury surface is as near as possible to the filament. When a globule has rolled out of its pocket, exposing a new surface for the anode, sometimes half a second elapses before the sensitiveness is again restored. This form of mercury tube is especially sensitive to the influence of a magnetic field.

The optimum or critical voltage of B becomes less after this Audion has been heated a little time, as though the heated mercury vapor began to act to increase the conductivity of the gas. This critical voltage keeps reducing as the vaporization proceeds, and with a sudden jar on the tube I can bring this down, one cell of B at a time, accompanied by a loud click in the telephone at each reduction. Sometimes a similar reduction of the B flux, amounting to as much as 25%, can be obtained with the double platinum wing type of Audion, by striking it smartly; or a sudden increase in the flux may be obtained.

The heating current when a large anode surface is used is less than that required to produce the same degree of sensitiveness with a small pool of mercury as anode. In general, the flux is quite proportional to the area of the anode, other conditions remaining unchanged. A mercury arc also may be substituted for the filament, but such an arrangement is apt to be noisy in the telephone.

When the hertzian oscillations are passed through the filament instead of through the gas they require to be of great intensity to give any response whatever. Any results from the added heating effect which they may contribute to the filament are quite insignificant. The response when Audions are connected in parallel, or series, is always less than for one used alone.

In a tube whose two-plane anodes are fitted on hinges and backed with small iron disks so that their distances from the filament can be regulated by an external magnet, I find the response to a long wave-length greatest when this distance is the greatest possible; while to a wave-length of about one half this the response is decidedly better when the wings are nearer to the filament. Of course the *B* flux is greater in this latter case, other conditions being unchanged; but the selective quality in this tube just described seems to be due to the regulations of the distance between anode and cathode rather than to other factors.

The manner in which the Audion should be located in the oscillating circuit, as well as many other considerations, shows conclusively that it is a "potential-operated" rather than a "current-operated" relay receiver. At the same time its advantageous sluggishness of action, as explained above, renders it additive in its response to the energy of an entire wave-train or even of a series of wave-trains. Hence its excellent and marked selective qualities.

A large number of experiments have been carried out with a view to reducing the filament heat necessary to give the enclosed type of the Audion the extreme sensitiveness which now characterizes it. This is now attained at normal brilliancy of the filament, or a little below; never at excessive heats. Thus the life of an Audion should be that of an incandescent lamp of the same class of filament and voltage.

Filaments have been coated with alkali metals or salts, or vapors of these introduced into the tubes. Experiments along these lines and with various dissociable gases are being pushed with gratifying promise of our soon being able to achieve the present marked sensitiveness even at red heats, or of still further multiplying the sensitiveness.

Radioactive compounds, applied for example between juxtaposed metal disks and heated, give little encouragement. At the low voltages used no increase of conductivity by their means has been observed, although Swinton has found that a radium-coated cathode in a cathode-ray tube has a marked action in facilitating a luminous cathodic discharge, when the cathode is heated to redness. The mere presence of radium salt in the tube is insufficient to produce the effect.

Spontaneous ionization; that is, the ionization independent of the electric field, as for example that produced by the X-rays, does not increase the current flux. Only the ions produced by the electric field itself close to the cathode, and by the heat of the cathode, is effective.

It is required that the Audion be made with scrupulous care; a trace of impurity in the gas may produce surprisingly large effects in the potential drop across the variation layers. The presence of a mere trace of moisture may cause great difference in the behavior of a tube.

In all this work a bewildering host of new and puzzling phenomena is continually encountered. By its nature clean and pretty, fascinating in its ever new phases, gratifying in the efficiency with which it responds to the difficult demands of a new and intricate art, the Audion combines infinitely delicate matter and forces, at once offering rich fields for study to the physicist and delight to the practical man.

DISCUSSION ON " THE AUDION; A NEW RECEIVER FOR WIRELESS TELEGRAPHY," NEW YORK, OCTOBER 26, 1906.

Michael I. Pupin: I have had some experience in the constructing of detectors of electrical waves. I always call them detectors, because, as a friend of mine said the other day, there are so many various detectors now that one is tempted to believe that anything will do to detect an electrical wave. In the course of the development of the art of telephony, any schoolboy could make a telephone that would receive electrical impulses; so in wireless telegraph work, the number of detectors seems to be increasing indefinitely—good, bad, and indifferent detectors appearing indiscriminately. If there must be a new name for each new detector—a new name for everything that comes up in the course of the development of the electrical art—pretty soon the science of electrotechnics will be a maze of new names; and the learning of the names will be much more difficult than the learning of the facts connected with the art. For that reason I am opposed to new names. Although Dr. De Forest is very enthusiastic about the elegance of the name audion, I must say that I am not very much impressed by it. It is a mongrel. It is a Latin word with a Greek ending. If he had said acouion or acousticon it might have been better, but more difficult to pronounce.

This is certainly a new wave detector used in actual wireless telegraphy. The physics of the thing is old. It was Hittorf, who, over fifty years ago, in 1850, I believe, discovered that in a vacuum tube in which even very high electric tensions would produce no perceptible discharge, the heating of the cathode facilitated the passage of electricity to such an extent that a small electromotive force, a few volts, would produce perceptible current. I think that was the first observation of the kind. After that the number of men who engaged in this branch of fascinating research became legion. The literature of the subject is well given in J. J. Thomson's book on "Discharge of Electricity through Gases." I am much interested in the subject, because one of my colleagues, Professor Tufts, has made some interesting investigations in that field, particularly in regard to the passage of electricity through hot gases containing a spray of salts at ordinary pressures. Dr. De Forest devotes some attention to this subject in the first part of his paper; but for reasons which are evident from the paper, he abandons this form of, I wont say audion, but wave detector. He abandons it, because it is variable, and resorts to the vacuum tube detector described in the paper. I think that is a clever step indeed, because one can see at a glance that this wave phenomenon which he first observed in connection with the passage of electricity through a hot gas at ordinary pressures, through flames of arc lamps, etc., might exist also in vacuum tubes, and that one would expect here a very much greater steadiness and reliability, and that, of course, is one of the highest desiderata in any technical work, particularly in wireless telegraphy. In this Dr. De Forest seems to have been successful.

I should have been very glad if Dr. De Forest had given a brief historical account of the subject, and then a brief statement of the physical theory of the whole matter underlying his invention. I think the paper would have been very much more easily understood by those who are not well acquainted with this part of the electrical science. I think we all feel that the matter is somewhat outside of our ordinary lines of work; it is a new subject, a subject that has been so far mostly in the hands of physicists and not electrical engineers. I hope that Dr. De Forest will, in the final publication of this paper, contribute a brief history and a brief statement of the physical theory of the subject for the benefit of the members of the American Institute of Electrical Engineers. As Dr. De Forest states frankly, it is difficult to explain the phenomena that one meets with when one tries to make a wave detector from a vacuum tube with a hot electrode.

What we have there is the hot electrode from which negative ions recede, and then we have the cooler plate, which is negative with respect to the hot electrode. When external electrical tension is applied to these electrodes, we have a considerable leakage current. We call it a leakage current for want of a better name; it is an electrical current. This electrical current is steady, according to Dr. De Forest, and this, in fact, is the most remarkable point in his paper; it is steady under all conditions, no matter whether electrical waves strike the oscillating circuit of which the tube is a part, or not. It is steady as far as a milliammeter can tell. It is not steady as far as the telephone can tell. Now, if the effect of the hertzian waves is to produce a unidirectional current, or rather if the effect of the wave is to rectify the hertzian waves—to let either the positive or negative parts of the wave pass through unhindered—why should we not be expected to perceive this in the milliammeter? We do not perceive it, and therefore we cannot suppose that these waves are rectified. The only other thing we can guess as probably happening is that the oscillation passes through the whole circuit; but on account of some effect upon the gaseous part of the circuit—the resistance or the diminution or increase of some of the other reactions—the original current is strengthened very much at certain intervals during one-half of the waves, and weakened during the other half, or strengthened during each side of the wave. This, as Dr. De Forest points out, is also impossible to believe, because the oscillations being so rapid, could not very well pass through the winding of the telephone in the first place, and in the second place could not be expected to produce a large magnetic effect upon the diaphragm; because magnetization and demagnetization of the permanent magnet in the telephone would not follow these rapid electrical oscillations. That seems to me to be one of the most difficult points to understand in the paper. That is the stumbling block in our understanding the *modns operandi* of the whole thing. Why does it operate? I have no explanation to offer. It would be presumptuous on my part to offer one, even if I had one to offer. If Dr. De Forest cannot explain it, I certainly cannot. But I have one suggestion to offer, and here it is: for quite a number of years, I have employed a telephone for detecting faint sounds, faint differences of potential, and faint currents. I find that the telephone is one of the most tricky instruments one can use. It will lead one to draw dangerous conclusions. The most misleading point in the detection of faint electromotive forces by the telephone is to distinguish between electromagnetic effects and electrostatic effects. The sensitiveness of the telephone has been estimated variously from 10^{-13} to 10^{-10} amperes. Now that is a very high degree of sensitiveness. It would be if it were correct. It is not correct. The telephone is not so sensitive as that, and I believe that those who made these determinations did not measure the right thing. If they had measured the current when they were determining the sensitiveness of the instrument, they would have found that the thing measured was not the current passing through the telephone coils, but in all probability the current which went through the body, all along the floor—the leakage current—which affected the magnetic force in the telephone which produced the sound. I have been misled that way quite a number of times. Whenever I see any one using the telephone in making observations I always look askance, and ask myself: has not this man been deceived in his calculations? I do not want to imply that Dr. De Forest might have been deceived in his measurements; I only want to say that when it is said the sound is heard, the question arises in my mind what produced that sound—is it the variation of the current which goes through the winding of the telephone, or is it the variation simply of the potential in the whole room, in his body, and in the windings of the telephone?

Percy H. Thomas: Apparently we have come across another example of apparatus illustrating the new theory in electrical science, an apparatus depending for its operation on the activity of corpuscles or ions. The audion probably will not introduce any fundamentally new principles when its operation is fully explained. The thing that interests us particularly at the present time is what is the nature of the ions and corpuscles. On this, scientists are not agreed, but there are a good many characteristics that are commonly accepted which will assist greatly in understanding such types of apparatus as the audion.

We may consider that electricity is either "corpuscles " or is connected directly with corpuscles. By corpuscles, or "electrons" as they are sometimes called, I mean those very small particles, approximately the 1-1000 part of hydrogen atoms with which we are all familiar. These corpuscles, then, when at rest, are static electricity, and as such are attracted by an electrostatic or "static" charge; that is, are sensitive to an electrostatic field but are not affected by electromagnetic influences. When, however, these corpuscles or particles are moved rapidly (and they move extremely rapidly, anywhere from comparatively slow velocities to nearly the velocity of light) they are the equivalent of electrical currents, and as such are subject to the influence of magnets, and themselves produce magnetism.

These corpuscles, figuratively speaking, may be looked upon as comets, or planets, or suns in space, for when they are free in a vacuum they move about under the influence of the various forces, electrostatic or electromagnetic, as may act on them, either in straight lines or curved lines, as the resultant force may require; when distributed through space filled with air or other gases, their free movements are impeded and they bump against one another and come in contact with the molecules of the gases, and consequently are unable to go steadily in the direction in which they may be attracted; and further, they often attach themselves to some atom or molecule or aggregate of molecules which again limits their motion.

As Dr. Pupin has stated, where you expect to utilize the motion of corpuscles, there is usually a great advantage in putting the apparatus in a vacuum. Like sodium or chlorine and many other materials corpuscles do not ordinarily exist in a free state. They are usually closely associated with molecules, in which condition they do not manifest their characteristic qualities. If you want to use them you must separate or isolate them. There are many ways of freeing them from matter. Corpuscles are frequently separated from air or other gases as, for example, by radiations from X-ray tubes; the waves that come from the X-ray tube, or the Crookes tube, by some mysterious process set free corpuscles from the gas molecules; or as stated in the paper the operation may be accomplished by letting ultraviolet light fall on certain metals. Corpuscles can be produced by the arc or a flame, as in the original audion, and in many other ways. They can be separated from solids and liquids, as in the Cooper Hewitt lamp. where they are produced in great quantities, in all probability from the electrodes themselves. The various starting methods used in Cooper Hewitt apparatus serve in different ways to initiate a freeing of corpuscles. This process is much easier to continue than to start. There are a number of well-known types of apparatus which are illustrations of the action of corpuscles.

First, the Geissler tube, in which by a strong electrostatic force, (that is by a high potential) corpuscles are either detached from the electrodes or separated from the residual gas which is purposely left in the tube so that there is an agitation of the gas atoms in the vapor space which causes them to emit light. Atoms of different substances give different colors of light.

Secondly, the Crookes tube, in which practically the same phenomenon exists, except that the residual gases are extracted so that the corpuscles though forcibly driven through the tube as before, give no light. They meet no obstruction and produce no visible effect, unless there is some fluorescent matter in the tube upon which they may impinge and cause it to give light.

Thirdly, Crookes tubes may be used for the purpose of getting waves, electromagnetic waves of some form or other, as in case of the common X-ray tube. Here the useful waves are produced by the impact of the corpuscles on an electrode of some sort.

Fourthly, the ordinary electric arc is presumably the forcing of a large number of these corpuscles from one electrode to another having them come in sufficient force and numbers to crowd back the atmospheric pressure and keep the gas molecules to one side. A large number naturally escape to the surrounding air, which is then said to be ionized.

Fifthly, the Moore vacuum tube which is in many ways similar to the Geissler tube.

Sixthly, the Cooper Hewitt mercury vapor apparatus, since it passes current through a vacuum must, according to this theory, be also a corpuscle operated device. Here there is a drawing of a large number of corpuscles from the negative electrode which in the case of the lamp excites the vapor in the tube, so that it will give light of its characteristic color. In the Cooper Hewitt type of apparatus there is this difference, however—that by virtue of the perfect vacuum and the large quantity of current or corpuscles, very little electromotive force is required to force them from the electrode; and there are other important differences. In the Crookes tube where the number of corpuscles in motion is very much smaller, a great deal of electrostatic force is necessary to separate them from the solid electrode.

Now in the audion we have a means of producing corpuscles, and we have a vacuum which allows more or less freedom of movement. We have a further means of controlling and directing these ions, that is, the additional battery electromotive force called *B*. The operation of the device depends upon the effect of the waves which come in on the transmission circuit which, in some way or other we do not now understand, so affect the action of the corpuscles which have previously been separated as to make a sound in the telephone.

I have spoken of corpuscles in connection with the audion as though they alone were the important factor while the paper speaks of ions. An ion is generally taken to be an atom to which is attached a corpuscle, or from which a corpuscle has been abstracted, and the determination as to whether the corpuscle acts entirely free of the atom is not finally settled.

The explanation which is suggested for the curious relay action of the audion, that it depends upon a virtual change of dielectric capacity in the vacuum space, is certainly an ingenious one and might turn out to be the correct one. There is one question I would like to ask Dr. De Forest. Do I understand that he presumes the action depends on the ionization of residual gases within the vacuum, or is the vacuum so perfect that the ions or electrons come from the electrodes themselves?

Lee De Forest: I think it is due to the ionization of the residual gases; the gases still exist in the lamp, because the vacuum is only that which obtains in all incandescent lamps.

Sewall Cabot: Dr. De Forest says: " The audion to a greater extent than any other responder is self-tuned. " Does this condition of self-tuning refer to change in the electrostatic capacity of the audion, thus altering the oscillation pitch to which the closed circuit having capacity and inductance is resonant? Or does it simply refer to tuning to the spark frequency on the assumption that with certain adjustments the audion will become most strongly responsive to a definite frequency of spark which is within the audible range of frequencies?

Lee De Forest: Both effects are really present. Where the tuning of the audion is regulated by changing the distance between the two electrodes, as in the last case described, where the two wings are hinged, and drawn to or taken from the filament by a magnet, we have there the change of capacity. In the other case, where the distance between these and the heating current or the filament remains unchanged, we merely vary the potential across the gap. It is rather difficult to explain this tuning effect on the ground of merely changing the capacity. This may be varied by the variation of potential difference but, as I have said, even though the wave frequencies of the two transmitters are as nearly the same as it is possible to make them, one spark frequency being 125 per second and the other 60 per second, the change of the battery *B* from 12 to 14 volts makes a great difference between the response of the audion to *A* or *B*. I think this selectivity is due rather to the integrating effect of the energy received during a brief unit of time. I won't attempt at this time to enter into a greater explanation than that. I think both effects are present.

Sewall Cabot: Is it true that the capacity of the audion can be changed through relatively large values so as to produce a considerable change of resonant frequency in a closed circuit when it is across the condenser? Thus connected, the capacity of the audion would presumably be very small with regard to the capacity used to bring the closed resonant circuit to the point of resonance if sharp tuning is obtained.

Lee De Forest: Yes; the capacity of the audion measured in that way is very small; a very small condenser put in shunt across it silences the response. Presumably, then, a considerable separation of the wings will not relatively change the tuning of the closed resonant circuit. The principal effect in tuning is with regard to the spark frequency.

J. B. Taylor: While I do not consider myself an expert on wireless telegraphy, it happens that I have made experiments on apparatus similar to that under discussion. I have operated a mercury-arc, with a single cathode and two anodes, from a storage-battery. The number of cells was no more than sufficient to maintain the arc, so that it was in a somewhat sensitive condition. In another part of the room was a 25,000-volt step-up transformer, and it was noted, after a spark from the transformer, that the mercury-arc had gone out. This was at first supposed to be only a coincidence; but the experiment was repeated a number of times with the same result, the arc going out immediately on the striking of the high-tension spark. Plainly, we had an arc detector for wireless signals similar to the audion. A note was made of the matter as something to be looked into in more detail at some future convenient time. I merely cite this to show that there is much resemblance between the mercury-arc, in fact any arc, and what in the audion I regard as an arc-stream between the incandescent filament and the plates.

The author's explanation of the *modus operandi* of the audion seems to me to be too complicated to stand much chance of being correct. When something new comes up for explanation we should take the simplest view of it first. Instead of immediately calling in the aid of ions, corpuscles, and other things of which we can have little physical conception, we should leave these as a court of last resort, to be called in only when simpler theories fail to account for the observed facts.

As described in the paper, there are many points in common between the audion and mercury-vapor apparatus. This resemblance, and some slight acquaintance with the mercury-arc induces me to offer an explanation with less of ions and more of the science of acoustics.

An organ-pipe may have the stream of air so directed that the pipe just fails to speak. Another pipe by sounding may cause it to speak, or even snapping the fingers may give the same result. The sound from another source carries just enough energy to upset the balance, to make a stable condition unstable. Similarly in the device under consideration this evening, the arc-stream is just on the point of vibrating and needs only a slight impulse to trip it. Here is an arc-stream in a very sensitive state ready to make a noise in the telephone, ready to vibrate or to start a new current-stream from another portion of the anode. The high-frequency wireless impulse need have only sufficient energy to make the stable condition of the arc-stream unstable. There is a short interval of time before the current in the arc becomes steady again, and it is in this interval that the telephone receiver gives its sound. I have not had the pleasure of listening to the audion; but I do know that a mercury-arc stream has a very definite vibrational period, as evidenced by the musical sounds heard in a telephone receiver.

This acoustical theory also may explain the sensibility to spark frequency. It being apparent that great sensibility would be obtained if the recurring impulse (as determined by spark frequency) coincide with the natural period of oscillation of the arc-stream itself.

The point is made that the reading of a direct-current meter shows no change, at the same time the telephone receiver gives evidence of fluctuating current. Dr. De Forest does not give the type, nor the sensibility of the direct-current instrument used. The current may increase or decrease, and the instrument not show it. If the sounds are due to vibrations of the arc-stream the resulting current would be very much like a direct current with the addition of a small alternating current, and a direct-current instrument will not show this so long as the alternating currents are relatively of small value.

I do not understand the analogy drawn between the hysteresis loss in ion; that is, put through a complete magnetic cycle, and what is termed, hysteresis loss in the audion. In the case of iron we supply a certain amount of energy, and a less portion of this same energy is returned, the difference being lost. In the audion I cannot see that there is stored energy in any form, so that it seems improper to speak of hysteresis losses in this case, merely because ascending and descending curves do not coincide.

Dr. De Forest makes a distinction between the relay action of the device as used by him, and the rectifying action of a similar piece of apparatus in the hands of others. This distinction seems quite proper, as the amount of energy available at the end of any commercial wireless transmission must be altogether too small to give any direct evidence of its existence to our senses.

Edward P. Thompson: A former speaker has alluded to the great importance of knowing the complete causes of the click in the telephone. Suspecting that an audible spark is produced in the telephone, sometimes, by the leakage of the oscillations to the diaphragm, I used a telephone casing without any magnet or diaphragm, providing the smallest possible spark-gap inside, by two wires almost in contact. By using this spark-phone instead of the telephone, but at short wireless telegraphic distances only, the same click was heard, and it was loud, because the sparks were produced in a small confined space close to the ear.

The probable conclusion is that the click in the telephone, although usually produced by electromagnetic action, may also be the direct sound of a very small and even invisible spark. Caution should be taken to experiment at short distances only, for it is obvious that the so-called spark-phone consists of a hertzian spark-gap detector in a confined space, with a listening opening to be placed close to one's ear.

Frederick K. Vreeland: While listening to this paper I was impressed by the striking similarity between some of the phenomena Dr. De Forest has pointed out, and certain actions that occur in electrolytic cells. We know it is quite the fashion now to point out the analogy between the behavior of electrons or ions in a gas and the behavior of the ions in an electrolytic solution; and although these analogies will not always bear the test of strict scientific scrutiny, they are sometimes very suggestive. Dr. De Forest has pointed out that in this audion there is a production of ions in the neighborhood of the hot filament, and has also shown that these ions are concentrated mainly in the vicinity of that filament. The ions in this case are produced by the heating of the filament. But if we take an electrolytic cell—for example, a pair of platinum electrodes immersed in acid—and connect a source of electromotive force across it, we shall also get a collection of ions on the anode and a collection of opposite ions on the cathode. The electrodes are said to be polarized. The distribution of potential in the electrolytic cell is somewhat analogous to that in the vacuum tube of the audion, and we can reproduce some of the phenomena that Dr. De Forest has called our attention to. For example, Dr. Pupin discovered years ago that if we take such a cell with very small electrodes, connect a battery in series with it and polarize it, that that combination of cell and battery is capable of rectifying an alternating current. The current will flow through it in one direction, but it will not flow through it in the other. Now, that is a rather close analogue to the arrangement of Professor Fleming, to which Dr. De Forest has called attention—his "oscillation valve," as Prof. Fleming called it. As you will remember, he took one of these hot-filament tubes and connected it in series with a source of electromotive force and a galvanometer, and he got a rectification. He explains that phenomenon if I remember rightly, by the fact that the negative corpuscles, being so much smaller and more mobile and having a higher velocity, are more easily set in motion than the positive electrons which are gathered at the other terminal, and consequently the current will flow more readily in one direction than in the other.

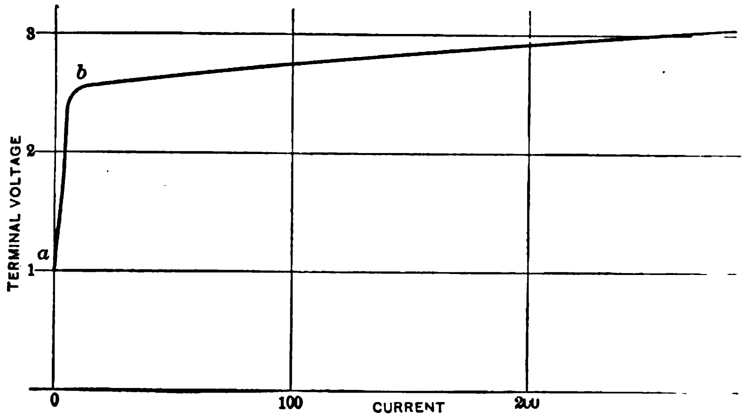

FIG. 1.

Now, regarding the "polariphone" receiver, if Dr. Pupin had been in the position I was in when I coined that name, I think he would have found it awkard to say "An electrolytic wave detector which operates by anodic depolarization." Polariphone is not quite so beautiful as audion, but it suggests the fact that the thing works by polarization and that the result is a sound. In the polariphone cell there is a very minute anode, and usually a larger cathode, and the cell is polarized by a dry battery. As you increase the voltage across the cell, at first you get no current, but when you reach a certain point a current will begin to flow; very minutely, it is true, but still it is a current, and that is at a point below the voltage ordinarily known as the decomposition voltage of the electrolyte, which is about 1.7 volts. The current commences at a point below that and gradually increases, the curve running almost parallel to the voltage axis, showing a small increase of current for a large increase of electromotive force, and finally reaching a critical point *b* where the curve turns over and you get a large increase of current for a small increase of electromotive force. If you polarize the cell to about that point it is sensitive to electrical oscillations, just as the audion is. These oscillations pass through the cell, depolarize it, and as a result of the depolarization, the counter electromotive force is diminished and a large current flows from the battery and gives an impulse to the telephone. Comparing this with Dr. Pupin's rectifier, we find a very similar relation to that which appears in the comparison of Dr. De Forest's audion with Professor Fleming's oscillation valve. It is vastly more sensitive and it performs a function which is not rectification—it is rather a relay effect, such as Dr. De Forest ascribes to the audion.

As to the question why the current does not affect the ammeter. I ask Dr. De Forest if it is absolutely certain that the current which affects the telephone is not a unidirectional pulsating current? The reason I ask this is that in the polariphone receiver you can get by suitable adjustments a similar phenomenon—you can get a very distinct and even loud signal without any increase of current which will affect the instruments ordinarily used for measuring these currents. We all know the telephone is an exceedingly sensitive instrument, even discounting the figure that Dr. Pupin repudiates. Instead of saying that it is sensitive to 10^{-13} ampere, suppose we say it is only sensitive to the millionth of an ampere. That is a very conservative estimate. Telephones are certainly sensitive to that current. A current of a millionth of an ampere would not affect any of the instruments that one would be likely to use in measuring such an effect.

Lee Deforest: I think that statement is correct.

Frederick K. Vreeland: Is it not possible you did have a unidirectional pulsating current sufficient to affect the telephone and not sufficient to affect the instrument you were using?

Lee De Forest: That is conceivable with extremely faint impulses, but at the same time I got signals which could be described as tremendously loud in the telephone, and no change of deflection, so I had no reason to suppose that as these signals became weaker in the telephone they would become unidirectional. There was no reason to suppose they should, when they are weak, give an effect entirely lacking when they are strong.

Frederick K. Vreeland: Then you incline, as I understand you, to the belief that the currents in the telephone were really alternating currents and did reverse.

Lee De Forest: Yes.

Frederick K. Vreeland: Then as Dr. Pupin says, that is an interesting point.

I do not set forth these analogies as strictly scientific parallels. I do not know just how far we could push them into a refined analysis of the question, but they are certainly suggestive, and I think they tend to crystallize our ideas as to the relation between the ionic phenomena in gases and those in electrolytes.

Lee De Forest: Dr. Pupin's opening remarks may serve as an argument why the study of Greek and Latin should be thoroughly introduced into our engineering schools. My knowledge of Greek is almost nil; I knew, however, that "aud" was of Latin and "ion" of Greek derivation. But they are both expressive. Where we use a term one hundred times a day, it is necessary to have something brief; we could not expect the wireless telegraph operators to use a long technical description of the apparatus in speaking of it, and when several types are in use it is necessary clearly and briefly to distinguish them.

As to why the milliammeter or sensitive direct-current instrument would not show any deflection at the time the telephone responded, we know that the sound we hear in the telephone reproduces of course the spark frequency. These impulses if they are all in one direction, and sufficiently close together and are of sufficient intensity, must produce an effect on the sensitive direct-current instruments. The only reason why they do not produce an effect must be that they are alternately in one direction and the other. With an oscillograph we would find out just what their curve is. I hope some day to do this. They are undoubtedly alternating, rather than pulsating. I hope to have the privilege of showing the audion in operation to some of the members of the Institute, and letting them hear the signals. I would like Dr. Pupin especially to hear them. The intensity of the sounds is at times so great that he will surely admit that they are caused by an electromagnetic current flowing through the telephone, and not by electrostatic effects in the telephone between the core and the diaphragm, although the latter effect undoubtedly exists.

As Mr. Vreeland says, there are a number of analogies between the audion and the polariphone. They both employ ions or corpuscles, as the case may be, and the forms of the saturation curves, current and voltage curves, etc., are sometimes similar in both cases I believe, however, that the analogies are not sufficiently close even to be discussed by lawyers in patent litigation!

DISCUSSION ON "THE AUDION" AT THE PHILADELPHIA BRANCH, November 12, 1906.

C. D. Ehret: Will Dr. De Forest please state the difference in principle and action between this audion and the Fleming rectifier, whose structural circuits so closely resemble those which he has placed on the blackboard

Lee De Forest: In the first place, Fleming took the old type of tube (see Fig. 1) which was produced in 1882, and which Elster and Geitel had found would rectify currents. Fleming built a cylinder which had been used by Edison, like this:

Fig. 1 shows the positive and negative connections of the battery, with a direct-connected galvanometer, *G*. There is a potential difference between this cylinder and the negative end of the filament in the Fleming rectifier, and, inasmuch as the negative ions are travelling from the hot to the cold body, there is a local current passing through *G* all the time. Thus only the positive half of the current oscillation can pass across the gap, the other half being choked back. By using intense waves and a sensitive galvanometer here, Fleming was able to increase the deflection. The value of such a device as a wireless telegraph receiver is nil. Exceedingly powerful signals are required to affect this galvanometer at all. Put a telephone in the circuit, and if the signals are sufficiently intense you can detect the pulsating currents in the telephone. But it is not practicable, in commercial wireless telegraphy. But now introduce an external electromotive force in the lead to the cylinder and connect the positive terminal with the wing. This increases the positive potential of the plate. The negative of this battery, "*B*," must be connected to the positive of battery "*A*"; then we get the full trigger or relay effect of the hertzian oscillations, which I can briefly call the "variation layer effect," whereby the hertzian

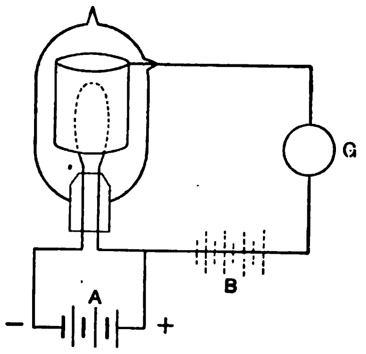

FIG. 1.

pulsations passing across the gap, control the variation layers before the electrode so that the local current flowing all the time has superimposed upon it alternating currents, whose source of energy is the local battery. These pulsations affect the telephone to a marked degree. In Fleming's case we have simply a hertzian-wave motor, and the hertzian wave merely acts with its own energy to cause deflection of the galvanometer armature. In the case of the audion with the two wings, the difference is still more marked, for we have a very marked *decrease* in the local current flow. The hertzian oscillation being applied to this insulated wing, produces now an effect not heretofore described. It causes a decrease in flux, but on top of that is the variation layer effect which I have just described, and which is indicated in the telephone. In a word, the chief difference is this; with the Fleming rectifier we have a hertzian rectifier, and here in the audion we have a relay.

C. D. Ehret: In the audion, is there always a normal flow of current from the battery *B* through the telephone.

Lee De Forest: Yes, always; but superinduced upon this are the alternating currents due, apparently, to the alternating changes in the variation layers.

C. D. Ehret: How do you connect the audion in a tuning circuit. You say it is a potentially operated device.

Lee De Forest: It is connected as shown here in the two-wing type (See Fig. 2). The two wings are connected to one leg of the

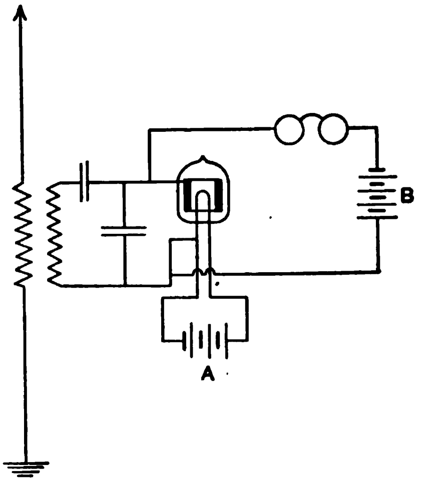

Fig. 2.

closed oscillating circuit, or we may have the antenna connected to the insulated wing, and one end of filament connected direct to earth. It makes a difference in the responses how the audion is connected in the oscillation circuit. If it is connected as shown here, the higher potentials are always applied to the wing, and the lower potential to the filament. The wing should have the maximum potential impressed upon it.

W. E. S. Temple: What is the voltage of the filament.

Lee De Forest: For convenience I use a 6-volt lamp; from 4 to 6 volts, using generally three cells of storage-battery. I started with 110 volts and then decreased it, finding high voltages impracticable, as one hears always a great noise from the dynamo at the power station. The battery "*A*", varies from 4 to 8 volts at the outside, and battery "*B*" from 6 to 18 volts. The current across the gap is very small, and I employ a small set of dry batteries the life of which is at least six months.

H. C. Snook: In connection with the different sensitiveness whch has been noted with reference to the platinum filaments, and the carbon filaments, I would like to ask whether there has been any experimenting done with the tantalum filaments?

Lee De Forest: I am using tantalum filaments entirely; I think they are much better The temperatures are higher than with either the carbon or the platinum. I have never been able to use the tungsten filament, but I should think it might give better results than the tantalum.

H. C. Snook: Can you make any statement regarding the use of the oxides of the alkali earth metals coated on the cathode, similar to the work done by Dr. Wehnelt of Germany, who states that the saturation current with the oxides of the alkali earths is much higher than in the case of the elementary metals, or the carbon filaments?

Lee De Forest: The only thing we have done has been to coat them with the alkali salts of potassium and sodium. The life of the filaments is very short, but I presume they may yet be produced so as to be better than the tantalum filament; every consideration points that way.

E. F Northrup: Will you not tell us more about that relay connection. If there is a rapid tap of the key, how rapidly can the relay be made to respond? Because, if you get the relay to act rapidly, you will be able to do a great many things in controlling motion, etc.

Lee De Forest: We have never tried any signals more rapid than those required in the ordinary telegraph practice, about 35 words a minute. Of course the sluggish voltmeter can be seen to deflect even with an instantaneous connection. A relay will operate positively at such speeds with very slight force, and as far as the audion goes, it will at least allow a speed of 35 words a minute, and I presume that with an oscillograph it would reproduce perfectly oscillations of very high frequency. The telephone diaphragm does that.

H. C. Snook: Do you not think that the residue of the gas left within the exhausted envelope has something to do with this lag.

Lee De Forest: Well, of course, the gas has something to do with the phenomenon. If the exhausting process is carried too far, the audion loses its sensitiveness. The gas particles, rather than the particles of the metal dust, are the carriers. I do not believe the dust particles are controlling at all. This extreme lag, when the battery "*B*" is of low voltage, is a most astonishing thing. You cannot imagine the gas all concentrated in that space around the insulated wing, while the hertzian oscillation is passing, but there seems to be either an abstraction of the ions into this space, and a very slow resumption of their original positions, or else a complete de-ionization and a very sluggish reionization. The positive ions and negative ions unite and cease to be carriers; they are then nothing but air molecules. I have never been able to arrive at any adequate explanation for this lag. It is as puzzling as the after-glow in a cathode-ray tube. Here we have the converse effect. Of course the time is seconds instead of hours, but whatever conducting property the gas originally had, is taken away from it for a few seconds, although the forces that gave it that property are still existant.

I would like to know if any one present has ever come across any similar effect connected with the gas particles, or ions, call them what you will?

C. D. Ehret: What is the action of a magnet on this audion. Is it an improvement or a detriment?

Lee De Forest: It is a detriment ordinarily, but it furnishes a way of regulating the flux, which can be regulated in a variety of ways. When the audion is put in a strong field at right angles to the flux of the ions, the ions tend to follow the magnetic lines of force. A great many will then go outside and do not strike the wings at all, so that if you have too great a flux, you can reduce that flux by the magnet and restore the sensitiveness of the audion. As far as I have gone, it seems that the magnetic effect is more pronounced, when receiving low-frequency oscillations than high frequency oscillations, which gives us a new method of tuning.

James Haywood: Can Dr. De Forest tell us what measure of efficiency this instrument has, as compared with former receivers. In other words, how much farther can you transmit a wireless message by using the audion?

Lee De Forest: I wish I could say that the audion is " 865¾ times " as sensitive as any other receiver, or even eight times, but all I do say is that the audion is more sensitive than the "electrolytic"; the same signals are louder than with the electrolytic, and the operator always prefers the audion because the signals are louder. I wont say you can cover greater distance, but I will say that for practical distances, the signals are louder on the audion than on the electrolytic.

George Breed: Dr. De Forest says that one of these wings should be connected with the high potential side of the converter on the antenna; how does he determine them?

Lee De Forest: One side of the oscillating circuit is connected to the filament and to all the ramifications of the circuits there attached. Here is the 'phone on the operator's head, a virtual ground, and consequently it is important to raise this other point of the oscillating circuit to its highest potentials. This insulated plate can be thus raised. The oscillating current is attuned by varying this shunting capacity and this self inductance, the same as with any receiver, but the tuning is decidedly sharper with the audion than with any other form of receiver that I know of.

A paper presented at a Meeting of the Pittsburg Branch of the American Institute of Electrical Engineers, November 20, 1906.

WIRELESS TELEGRAPH RECEIVERS

BY S. M. KINTNER

Improvements in wireless telegraph receivers have been much more numerous than in the sending apparatus. Since the first detector of Hertz, consisting of a minute spark-gap and loop of wire, used in 1887, there has been a very marked improvement. This improvement has not extended to the sending apparatus, for this apparatus is practically the same to-day as that employed by Hertz, differing mostly in magnitude and in the fact that one side of the oscillator is connected to ground.

Of the various detectors, the coherer is perhaps the best known. It was this device that gave wireless telegraphy such an impetus. Marconi used it in nearly all of his early work. The coherer, it is well known, operates by the breaking down of insulating films separating small metal particles. It is thus evident that the coherer is dependent upon voltage for its operation, the quantity of current involved entering only as a secondary function. The coherer can be looked upon as a sensitive trigger, delicately set, which after operating requires to be reset before it is ready for the next impulse. It is a delicate and treacherous device, and, is usually set aside by investigators just as soon as they have any other device to substitute for it.

In 1899, Professor Fessenden and the writer were conducting some wireless telegraphy experiments, and during these investigations the writer tried to persuade Professor Fessenden to try a coherer in some of the tests, but he was unwilling to do so. He remarked at that time, when every one was singing the praises of the coherer as such a remarkable and satisfactory instrument, that it was a waste of time to use it, as it was incorrect in principle. He advocated then some form of current-operated device, a device which would utilize more of the collected energy than was possible with the coherer. In these early experiments, a form of galvanometer consisting of a small ring suspended at an angle of 45° to the plane of two field coils, as shown in Fig. 1, was employed.

This device was connected in the receiving circuit, forming part of a straight series circuit from the vertical antennae to ground. When the oscillating currents set up by the radiating electric waves were passing through the field coils *F*, *F*, a current was induced in the ring *R*. The ring would then tend to move and thus give indications of the presence of electric oscillations in the vertical wire. The amount of the deflections would be read with a reading telescope and scale from a mirror carried on the ring, as with an ordinary galvanometer.

This device gave quantitative results, while those obtained with the coherer were entirely qualitative and quite uncertain. Working with a device of a kind capable of giving quantitative values, even though possibly not so sensitive, was much better for studying various modifications of the sending apparatus, etc. With that old home-made instrument, some of the fundamental points that have since become standard practice were determined.

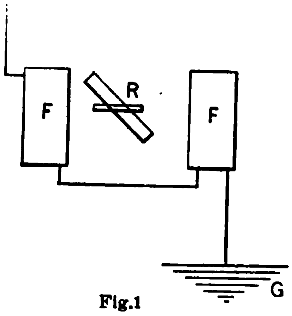

Fig.1

Unfortunately for the ring-form of galvanometer, it had one serious defect; the current in the ring was in nearly 90° phase-relation with the magnetic field producing it, resulting in a very small torque. But for the fact that the ring itself had an appreciable inductance for its own induced current, thus causing it to lag slightly, there would have been no torque. Attempts were made to increase the torque by various schemes calculated to change the phase of the induced currents, but with only moderate success. Very small iron wires were placed through the ring at right angles to the main field, thus tending to increase the inductance of the ring. In other trials the ring was split and terminated in small condenser plates, but with no material improvement.

After Professor Fessenden had left Pittsburg to devote all his time to investigating wireless telegraphy, the writer attempted for a time to carry on some investigations along similar lines In attempting to overcome the trouble with the ring and its phase-relation, an effort to produce a rotary field was partly successful. Fig. 2 indicates the method used to produce this field.

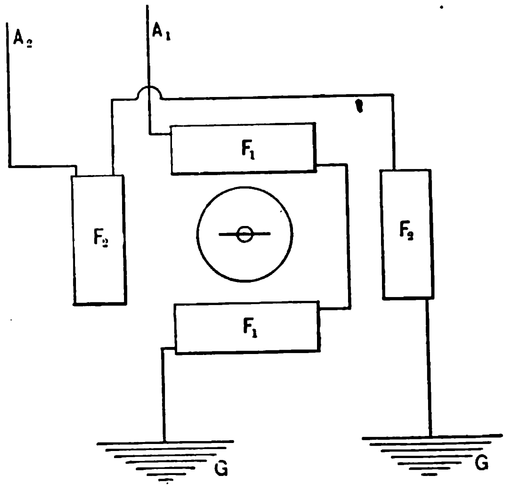

Fig.2

It will be seen here that a two-phase field is arranged and if currents of the proper phase are sent through it, a true rotary field will be produced. The two-phase currents were obtained by spacing two vertical antennae one-quarter wave-length apart. It was thus possible to tell the direction the waves were coming, as of course the direction of rotation depended upon which of the two verticals reached its maximum value first. The device was not very sensitive, probably because the field could not be so advantageously arranged as is desirable for induction motors. An effort to utilize exceedingly fine wire to concentrate the field proved a complete failure.

Marconi brought out a magnetic detector which operated on the peculiar physical fact that iron when passing slowly through its hysteresis loop, is very sensitive to a magnetic field set up by electric oscillations. This device is quite successful in service and is much more reliable than a coherer. In practice this device is arranged so that a small motor is rotating an iron core at a very slow rate in a magnetic field; the core is surrounded by the detecting loop connected in the receiving circuit; a secondary loop leads to a telephone, and the sudden changes in magnetic conditions of the iron due to electric oscillations set up by the received waves are indicated by small current changes in the telephone circuit.

Fessenden brought out what he called a hot-wire barretter that was quite an advance, particularly for quantitative work.

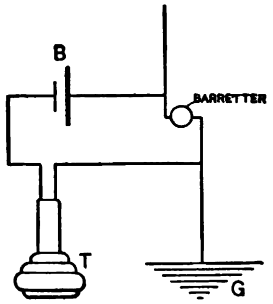

Fig. 3

This device has since been used for some investigations in telephone work and is very satisfactory for such service. The device consists of a very small loop of platinum wire, so arranged in a circuit that its change in resistance due to change in temperature caused by the oscillating currents is indicated in a telephone connected in circuit as shown in Fig. 3.

The size of the platinum wire and some of its characteristics are quite interesting. The small wire in the loop is only about 0.00008 in. in diameter and only about 0.015 in. in length. These figures seem almost incredible, but they are approximately correct. Such error as really exists is on the side of too large dimensions.

The Wollaston wire, by which name the above is known, is a composite wire of silver with a platinum core. The platinum is first drawn as small as possible and then coated with silver until a composite wire is formed having a section of which 99% or more is silver. This composite wire is then drawn down to very small dimensions, the platinum core being reduced in section at the same time. The silver is afterwards dissolved in acid at the places at which the fine section is desired.

An 0.00008 in. platinum wire has a resistance of 8450 ohms per foot, or approximately 10.5 ohms for 0.015 inches in length. The small mass involving, only 7.5×10^{-11} cubic inches of platinum requires only 0.0356 ergs to raise its temperature 1° cent., or one erg would increase its temperature about 30° cent., which would mean a change in resistance of approximately 12%. The above figures are assumed without consideration of the larger section of wire at the ends of the loop where the silver has not been removed. Unfortunately for the sensitiveness of this device, these terminals play a very important function, and tend to keep the temperature down, so that instead of a 12% resistance change it is quite likely that not more than 6% change in resistance really takes place. With such a small mass, its thermal capacity is very low, and it is thus able to follow changes of temperature at a very rapid rate. The device actually responds so rapidly that no trouble is experienced in distinguishing between the quality of several sparks, in the same way that one can distinguish each of several voices.

The drawbacks with this detector are, its liability to burn out and the difficulty of renewals. Burn-outs may result from lightning or from signals of great intensity. The forming of the loop is a very delicate operation and is done under a microscope.

The liquid barretter was the next important advance made in detectors. The liquid barretter differs from the preceding only in that an exceedingly fine liquid resistance is substituted for the metal resistance. This liquid resistance is best made by making use of the Wollaston wire again, and allowing it to dip for a very slight distance into an electrolyte. The electrolyte used is preferably a 20 to 30% solution of nitric acid. The acid serves to dissolve the silver and thus keep the barretter in operating condition should it become burned out by excessive currents.

It is a well known fact that the resistance between two concentric cylinders immersed in an electrolyte is equal per unit length to $\frac{C \log.}{2\pi} \frac{b}{a}$ where C is the resistivity of the electrolyte and *b* and *a* are the diameters of the two cylinders respectively. It will be seen very readily from the above formula that nearly all the resistance is located in the liquid surrounding the fine wire. Electrolytes have much larger temperature coefficients than metals, and thus a decided increase in sensibility is gained. In addition to the ohmic resistance change, there is a change in the polarization of the fine metal point. Fortunately, these are additive effects and tend towards sensibility.

The liquid barretter was discovered accidentally b Professor Fessenden while making some loops for the wire form of barretter. He noticed that a delicate current meter in the circuit with the loop that was having its silver dissolved off, was fluctuating in synchronism with a sending station some distance away. An investigation of the cause revealed the fact that the wire loop had broken and left two fine points dipping into the acid. That was the first form. Later tests showed that one point was supperior to two. Other than that, the principal development consisted in getting a good mechanical arrangement and testing a number of electrolytes. Nitric acid, as mentioned above, has proved the best, everything considered, though several other solutions such as H Cl, K O H, H_2SO_4, have been satisfactory.

This detector is the best that has thus far been developed. A number of detectors are at present in use which are fundamentally the same as the liquid barretter. The fact that it has so many imitators is evidence of its good qualities.

One of the most notable detectors, a modification of the barretter, is that one in which the battery is made a part of the detector by using a containing cup made of a metal electrochemically positive to the fine platinum point. This is accomplished practically by using a zinc cup.

The barretter and its various modifications form a class of detector that is very satisfactory. It is sturdy, despite its almost microscopic dimensions; it can be operated when mounted on a rolling ship, or when the table on which it is supported is moved suddenly or even dropped a distance of a foot or so. In the event of breaking the small platinum wire at the point of immersion, it is a matter of a moment to screw down more of the wire and thus form a new point. The cell operates best when a pressure of approximately 1.6 volts is impressed across it.

The small point should preferably be connected to the anode, as it is somewhat more sensitive with that arrangement, though it is operative with either connection. The current changes are of the order of 1×10^{-6} amperes, but this is ample for a telephone, though too small to operate a relay with certainty

This detector, like the hot-wire detector, recovers very rapidly and consequently enables one to distinguish between each of several sending stations.

A paper presented at the 211th meeting of the American Institute of Electrical Engineers New York, November 23, 1906.

TRANSFORMATION OF ELECTRIC POWER INTO LIGHT.

BY CHARLES PROTEUS STEINMETZ.

I. GENERAL.

Of all the achievements of modern science or engineering the production of light is the least creditable. In the transformation of electric power into mechanical power, as in the electric motor, or the transformation of mechanical power into electric power, as in the dynamo, efficiencies far higher than 90 per cent. have been reached, the transformation is practically complete, and all further advance must be expected in the direction of increased reliability of operation, decreased size and cost, etc. Even in the steam-engine or steam-turbine, 60 per cent. or more of the available energy of the steam as it issues from the boiler is recovered as mechanical work.

In the production of light, the efficiency of the incandescent lamp is measured by a fraction of one per cent., and if we should succeed in increasing the efficiency of light production tenfold—get ten times as much light as we get now from the same power, the efficiency of production of light would still be ridiculously low; and even with a hundred times its present efficiency, it probably would compare unfavorably with efficiencies that are familiar to us in other electrical apparatus. While the incandescent lamp is more efficient than the gas-flame or the kerosene lamp; that is, gives less heat with the same light, still its efficiency is extremely low. The main reason for this condition appears to be that in the incandescent lamp or the ordinary carbon arc-lamp the light is really a by-product; that is, the lamp converts electric energy into heat, and only incidentally produces light.

II. LIGHTING BY INCANDESCENCE.

If energy is impressed upon a solid or a liquid, as by passing an electric current through a carbon filament, and no other work done, the body is heated. This energy must be given off again; it is given off partly by conduction, but largely by being radiated from the incandescent body. By increasing the power, the amount of radiation increases; and there are changes in the quality of the radiation too: first appear radiations of very great wave-length or very low frequency, then, with the increasing power, higher frequencies appear; that is, the wave-length of radiation becomes shorter. In other words, in addition to the long waves which appear in the beginning, shorter and shorter waves appear: not only the total amount of radiation increases, but also the variety of waves increases and, ultimately at a certain amount of heat given to the body or at a certain temperature, waves as short as 750 $\mu\mu$ appear. These are noticeable to the eye as dark-red light. Then still shorter waves appear gradually: orange, yellow, green, blue, lavender, violet. Beyond wave-lengths of 400 $\mu\mu$, the waves again become invisible, as so-called ultraviolet waves.

Of the infinite variety of waves radiated by a heated body—from the long heat waves given by liquid air to the shortest ultraviolet waves, many octaves of wave-length in all—somewhat less than one octave is visible to the eye. These wave-lengths are useful as light; the rest is wasted energy. A parallel would be found in music, if instead of six or eight or more octaves, as given by musical instruments, less than one octave were audible. To this fact is due the very low efficiency of light production by heat: of the total system of radiation only a very narrow range is useful, less than one octave.

Of these useful rays, the visible three-quarters of an octave, none appears until the temperature is fairly high. Below that, only the long waves appear. That means the average wave-length of radiation decreases with the temperature. Or, with increase of temperature, not only the existing waves become more intense, but shorter and shorter waves appear, and the intensity maximum moves toward a shorter wave-length. With increase of temperature, the percentage of visible radiation thereby becomes greater and ultimately reaches a maximum, or the efficiency would be the highest when the maximum intensity lies just within the visible octave. Where this maximum may be is unknown, but it is beyond the temperature of the crater of the arc, possibly somewhere between 4,000° and 5,000° cent. At that temperature the efficiency of the incandescent light is a maximum, and probably from one-quarter to one-half watt per candle-power. But even then the efficiency is not high, 5 to 10%, or thereabouts. It follows, however, that even if we could raise the incandescent body to the temperature of maximum efficiency, we would still get only about 5 to 10% of all the energy as light. The other 90% would be ultraviolet, chemical or actinic rays, X-rays, or long heat-waves. There is thus an absolute limit to efficiency of lighting by incandescence.

The higher the temperature the greater the light efficiency of an incandescent body. Carbon is apparently the most refractory of all substances—its boiling point being somewhere near 3,500° cent.—so as incandescent body can be raised to the highest possible temperature and the incandescent crater of the carbon arc so is the most efficient source of light by incandescence. It is still somewhat below the temperature of the efficiency maximum.

Incandescent lighting is effected by the electric current, either by raising the temperature of the light-giving solid body, a lamp filament, by passing a current through it, or by passing the current from it into another body. In the latter case the temperature of the boiling point of the material is reached, and the crater of the carbon arc lamp, at the highest temperature which can be reached, so gives incandescent light of maximum efficiency, probably not very far from half a watt per candle-power. But the large amount of energy, which is conducted away by air currents, etc., greatly reduces the actual efficiency of the carbon arc below this value.

When producing light by passing an electric current through the conductor, as in the incandescent lamp, no such efficiency can be reached. Here carbon is also chiefly used. The higher the temperature of the incandescent-lamp filament, the greater is the efficiency; but the limit of the temperature is not the boiling point of carbon, 3,500° cent., but far below that; it is the temperature where evaporation of the filament becomes so rapid as to limit its life below economical requirements. This is probably not very far from 1,800° cent. Far below the boiling point, evaporation takes place: water evaporates at ordinary temperatures; even below the freezing point snow and ice evaporate very noticeably. An incandescent carbon filament evaporates, thereby decreasing in cross-section, and increasing in resistance; the current decreases, therefore the temperature decreases and with the temperature the efficiency decreases. As the condensed carbon vapor blackens the globe and obstructs the light, another decrease of light results from absorption. Thus efficiency has to be sacrificed in the incandescent lamp to get good life, and the specific consumption of electric power, instead of being one watt per candle-power (as in the case of the arc lamp) becomes as high as four watts per candle-power.

The arc, then, is the more efficient illuminant. But its efficiency is still low, and here there has been a similar result; to increase the life, the efficiency has been decreased by enclosing the carbon arc, in the present long-burning lamp. Increasing the efficiency of the arc by reducing the conduction of heat by a decrease of the diameter of the carbon has also been tried, with the same result—exchanging efficiency for life.

In the incandescent lamp, the problem of increasing the efficiency can be attacked in two ways. One way is to replace the carbon by a material which has a lower vapor-tension at high temperature. While carbon has the highest boiling point, it is not the boiling point nor melting point which is of importance in a lamp filament, provided that this point is sufficiently high—it is the vapor-tension far below this point.

For instance, the metals osmium, tantalum, wolfram (tungsten) have a lower melting point or boiling point than carbon, but they have at the same high temperature a lower vapor-tension, due possibly to the much greater atomic weight and so much greater heaviness of their molecule (atomic weight of carbon, 12; osmium, 191; tantalum, 183; wolfram, 184). These metals can be operated at a higher temperature than carbon, and as lamp filaments they give a much greater efficiency than the carbon filament.

The efficiency of the incandescent lamp can be improved by replacing the carbon filament with a material which has a lower vapor-tension, and a sufficiently high melting point. Tantalum, osmium, wolfram or tungsten as materials for incandescent-lamp filaments, promise to revolutionize the incandescent lamp, by holding out fair promise of an ultimate efficiency of about 2 watts per mean spherical candle-power for tantalum, 1.5 watts for osmium, and 1 watt per mean spherical candle-power for wolfram—compared with about 4 watts per mean spherical candle-power for the carbon-filament lamp. The objection to these metal filaments obviously is the low resistivity inherent to metals, which restricts their use to relatively larger units or at least makes difficult the production of low candle-power sizes at customary voltages.

Another way of improving the efficiency of the incandescent lamp is by improving the carbon. The vapor-tension depends not only on the chemical constitution, but also on the physical structure. Ice evaporates very much slower than a mass of loose snow. Furthermore, it is possible to produce different forms, possibly allotropic modifications of carbon, of different rates of self-destruction. The product of carbonization of fibre or cellulose can not be run at as high a temperature with the same length of life, as can carbon deposited from hydrocarbons, as benzol or benzine, by high temperature. Experiments with carbon at very high temperatures show probably greater variations in the character of carbon, than with any other material. Possibly this is due to the tendency which the carbon atom has more than any other atom, of polymerization. and especially ring formation, which results in the formation of allotropic modifications of carbon, having the greater stability of such polymerized molecules. So at the boiling point of carbon, the carbon deposited from hydrocarbons converts, under the influence of atoms which can enter and leave the carbon chain, into an allotropic modification having pronounced metallic characteristics, as elasticity, a positive temperature coefficient of resistance, etc., and very great stability, so that as a lamp filament this form of carbon can be run up to a considerably higher efficiency, in the so-called "metallized filament."

III. SELECTIVE RADIATION OF SOLIDS.

Most incandescent bodies give the same, or approximately the same law of radiation, that of the so-called "black body"; that is, at the same temperature the intensity of radiation varies with the wave-length or frequency in the same manner, somewhat similar to that shown by Curve I, Fig. 1 * with a maximum at a certain wave-length. At higher temperature, Curve II, a similar intensity curve exists, with the maximum at shorter wave-length, or higher frequency, so that the intensity within the visible range, shown shaded in Fig. 1, is a higher percentage of the total radiation; that is, the efficiency of light production is higher.

If, however, a body could be found which at the temperature

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* These curves, drawn with the logarithm of the frequency of radiation as abscissas, are only illustrative, and not quantitative nor based on experiment, but merely illustrate the statements made above.

corresponding to Curve I, gives an abnormally low radiation outside of the visible range, as illustrated by Curve III, or which with normal radiation in the invisible range gives an abnormally high radiation in the visible range, as illustrated

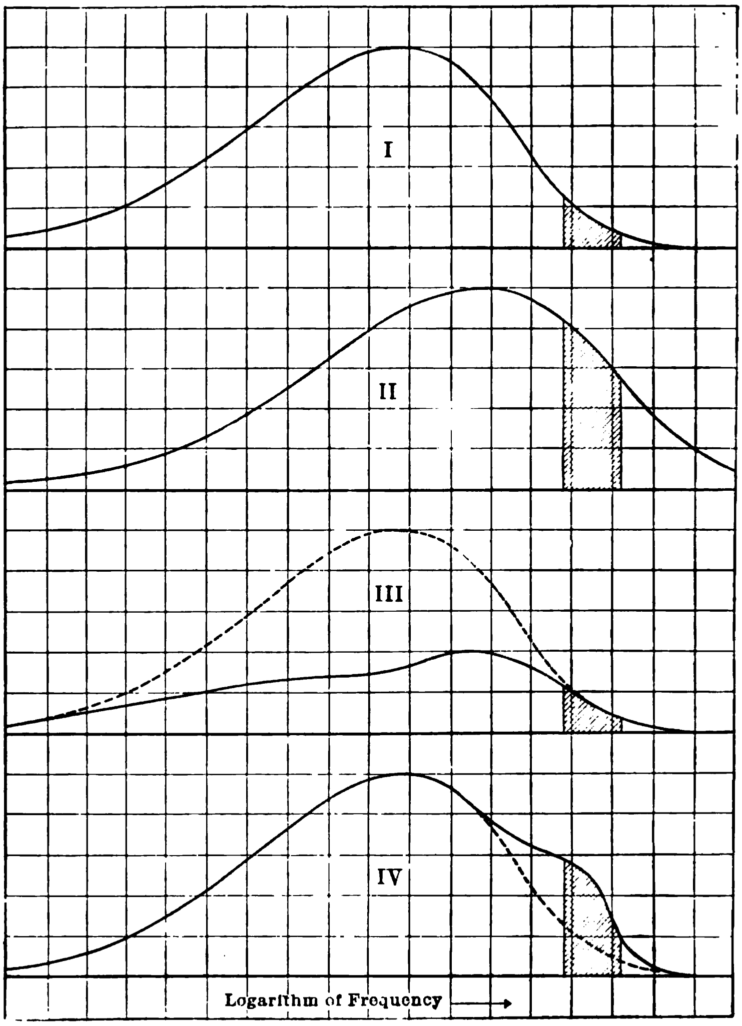

Fig. 1.

by Curve IV, then in either case the visible radiation would be a greater percentage of the total radiation than corresponds to the temperature; that is, the efficiency of light production would be higher than that of a black body at the same temperature. Theoretically such a body with selective radiation might give an efficiency higher than the absolute maximum of light efficiency of black-body radiation.

Either of the two cases; abnormally high radiation in the visible, and abnormally low radiation in the invisible range, may give the same shape of intensity curve, the only difference being that in the first case the total radiation per unit surface is higher, in the last case lower than that of a black body at the same temperature. That is, with the same amount of light radiation and the same efficiency, in the last case the radiating surface is greater than in the first case, and this may give a criterion to decide between the two alternatives.

With such selective radiation, there may be a different distribution of intensity throughout the visible range, and so the color of the light may differ from that of an incandescent body. With abnormally high radiation in the visible range, the increase of intensity is probably greatest in the middle of the visible spectrum; with abnormally low radiation in the invisible, the decrease of intensity is least in the center of the visible spectrum. In either case the tendency is towards preponderance of the wave-lengths in the middle of the visible spectrum; that is, the greenish-yellow, as characteristic of such selective radiation, and apparent in the Welsbach mantle. Typical of such selective radiation is the lime cylinder of the calcium light, and possibly the flame of burning magnesium.

With gas as illuminant, a very great increase of efficiency has resulted from the use of selective radiation; as found in the Welsbach mantle.

In electric lighting, the Nernst lamp probably represents the first attempt, on a large scale, of improving the efficiency of light production by selective radiation. It has not been as successful as in gas lighting, since the efficiency of the Nernst lamp does not differ much from that of the carbon incandescent lamp, while the efficiency of the Welsbach mantle is many times higher than that of the ordinary gas flame. The reason probably is that with a very inefficient illuminant, as the gas flame, the additional light given by selective radiation may increase the total light several fold, while the same amount of additional selective radiation with a relatively far more efficient illuminant, as the incandescent lamp, is a far lower percentage of the total visible radiation. Or, to illustrate, the additional shaded area, between the dotted and the drawn line in Curve IV, Fig. 1, increases the efficiency threefold, while the same additional area, added to the shaded area of Curve II, would not materially increase the efficiency. That is, the increase of efficiency by selective radiation of an incandescent body becomes less with a more efficient illuminant, and selective radiation may greatly increase the efficiency of inefficient illuminants, but not so much that of efficient illuminants, so that the hope of very greatly increasing the efficiency of light production by selective radiation of solids does not appear very strong. However, some of the recent very efficient incandescent-lamp filaments, as tungsten and osmium, may owe their high efficiency partly to selective radiation; that is, may give light not only by incandescence, but also by luminescence.

IV. ELECTROLUMINESCENCE OF VAPORS AND GASES.

The problem of efficient light production consists of producing radiations; that is, vibrations of the molecules or atoms of the light-giving body, of frequencies within a limited narrow range, that of visible radiation, and as few vibrations as possible outside of this range. When heating a solid body, the energy put into it as heat sets the molecules or atoms in motion, in vibration. Where they are close together, as in a solid or liquid, they cannot vibrate freely; each cannot have a period of its own, just as all the different grains in a sand heap can not vibrate simultaneously as do the molecules of a tuning fork, but the vibration is irregular. All you can get is a mixture of all kinds of vibrations: not a tone, but a noise. To get a tone requires a body which can vibrate freely without restraint; that means a gas; as the gas molecules are free, they can execute free vibration. A vibration of a definite pitch, definite frequency, that is definite color of light can be produced only in a gas or vapor. But when heating a gas or vapor, the energy put into it appears not as vibration of the molecules, except perhaps indirectly at extremely high temperature, but as rectilinear motion or pressure. The molecules move faster in their rectilinear paths, and so strike the boundary at higher velocity; the pressure of the gas rises by increasing molecular velocity, that is, increasing temperature, but the vibration of the light radiation does not appear. So heat, while making a solid or liquid incandescent, does not make a gas incandescent or luminous but merely increases its pressure.

There are methods, however, of setting the gas molecules in vibration. By chemical reaction or electric stress, gases become luminescent; that is, the molecules of the gas are set in vibration. For instance, if the gas is used as a conductor of electric current, then the molecules of the gas are set in vibration, and we find a definite period of vibration, or a number of periods or frequencies, in which the gas molecules or atoms can vibrate; that is, gases give line spectra. So in a mercury arc, the molecules vibrate not as those of a solid body, but only with a small number of wave-lengths. Many of these are within the visible range, within the fraction of an octave which is seen by the eye: one is of a greenish-yellow; another wave is green; another is dark-green; another is blue; two vibrations appear as violet, and numerous vibrations excited by the mercury arc are in the ultraviolet, very short.

Here results a definite rate of vibration, practically independent of the temperature. The mercury vapor vibrates at that frequency which gives that particular yellow light, and that particular green light, etc., whether the temperature is high or low, and the wave-length does not change as it does with the radiation of a solid incandescent body; it is fixed by the nature of the molecule, so that the temperature has no direct effect. It has an indirect effect in so far as at higher temperature, vibrations may become more prominent, which are small, or almost non-existing, at low temperatures. For instance, in mercury vapor the lowest frequency is that giving the greenish-yellow line, but no appreciable amount of vibration is so slow as to give red light at ordinary temperature. When you raise the temperature very high (but still below the temperature of the incandescent-lamp filament), then the mercury molecule begins to execute a slow vibration, which gives an intense red light, and red lines appear in the mercury arc; with increasing temperature it gradually changes its color from green to white to red. Here we have a particularly interesting illustration that for luminescent vapors or gases the law of the black-body radiation does not apply. In a solid black body, with increasing temperature, the mean wave-length decreases, shorter waves appear, and the light changes from the red over yellow toward white. Now it happens that with mercury vapor at the higher temperature, a slower vibration, or longer wave, of red light, increases in intensity faster than the short vibrations, and the light changes from green to white and ultimately to reddish-pink at high temperature. It is a mere incident, but it shows that temperature has no effect directly, only indirectly, in that particular rates of vibration may appear with change of temperature, may become more or less prominent, depending on the material which luminesces.

As a rule, then, it can be said that such an arc or a luminescent gas or vapor is more efficient as a producer of light, the lower the temperature. This is just the reverse of the solid incandescent body. In a solid body the higher the temperature the larger a percentage of radiation is within the visible range, and the higher the efficiency. In a gas or vapor, a certain definite vibration is impressed directly by the electric energy or the chemical energy which sets up the oscillation; the heat which is produced is incidental, is a by-product and therefore a waste. The lower the temperature the less waste of energy takes place as heat, and the more efficient is the luminescent gas. With a luminescent gas the heat is a by-product which we want to decrease just as in an electric motor or generator; that is, the lower the temperature the better. This is one reason why the mercury arc is extremely efficient; it has the lowest temperature.

Theoretically, there is no limit to the efficiency of a luminescent vapor. A vapor may be imagined which vibrates only with one particular wave-length, say a yellow line. That means all the energy put into it must be radiated at that particular wave-length, as yellow light, and therefore the conversion of electric energy into light would be 100 per cent., not counting the energy lost by heat convection or conduction. The latter can be made very small by enclosure in a vacuum. Complete conversion of electric power into light would so result, if all the spectrum lines were within the visible range. That is never the case. There is no definite law giving the percentage of energy which appears as radiation in the visible spectrum, and which appears outside of the visible range as ultrared and ultraviolet lines; but the position of the lines in the spectrum is an individual characteristic of the gas or vapor. The problem of efficient light production is to find a material having most lines in the visible range of the spectrum.

With mercury vapor which is set in vibration by the current, a very high percentage of the total energy is radiated in the visible range. With carbon vapor, the percentage of energy radiated in the visible range is extremely small. The carbon arc is extremely low in efficiency, practically non-luminous. Silicon also gives a practically non-luminous arc. Others, like calcium, titanium, etc., give a very high percentage of light within the visible range, and so a high efficiency of light production.

The color of light produced by incandescence varies from reddish-yellow at low temperature, to yellow, and approaches yellowish-white at higher temperature. Selective radiation of solids tends to superpose hereon a preponderance of greenish-yellow rays, without, however, greatly changing the color. With electroluminescence of vapors and gases, however, the color of the light depends on which of the spectrum lines happen to be most prominent.

Electroluminescence makes it possible to produce light of any color. This, however, greatly complicates the question of efficiency. As efficiency can no longer be considered the ratio of the power radiated within the visible range to the total power input, since the different parts of the visible spectrum have entirely different energy-equivalents: one candle-power of red light, or of violet light, represents many times more power which issues as radiation, than one candle-power of green or of yellow light. That is, the light-equivalent of power is a function of the wave-length. It is obviously zero in the ultrared; it is very low in the dark-red; and gradually rises to a maximum in the yellow and green, and then decreases again, becoming very low in the violet, and zero in the ultraviolet. One candle-power per watt as red light or as violet light may therefore represent a fairly high efficiency, while 10 candle-power per watt, with green or yellow light, would be a far lower efficiency. That is, the energy radiated in a beam of one candle-power red light probably is greater than the energy of a beam of 10 candle-power of green light.

This feature explains the impossibility of determining efficiencies of light by the measurement of physical quantities. Light is the physiological conception of some wave-lengths of radiation, but no physical quantity.

Where high economy of light production is the only, or the foremost consideration, spectra in which green or yellow preponderates are therefore selected; for instance as mercury, bluish-green in the mercury arc lamp—or calcium—yellow, in the flame carbon lamp. These two illuminants give high efficiency, but they give it by sacrificing the inefficient colors at the end of the visible range. But, unfortunately, the sun, as an incandescent body, gives the light of solids or liquids, and therefore gives all the radiations, with the red end of the spectrum specially prominent; and, since we call the sun white, the light from the mercury arc appears green, that of the flame carbon arc yellow, not the yellow of the incandescent lamp, but a pronounced monochromatic hue.

The mercury arc and the flame carbon arc are useful for cheap lighting, regardless of color. They also find an application for special effects due to their color. So the mercury arc is eminently suited for outdoor lighting in suburban districts where its effect on foliage and snow makes it superior to illuminants containing red rays and so intensifing the appearance of incipient death in the vegetation, and where the intrinsic brilliancy of illumination can be kept sufficiently low as not to show the objectionable effect of monochromatic light. The flame carbon arc finds its field in advertising, where its intense glare makes it especially suitable.

For general illumination, however, at least in this country, people have become educated to require as close an approach to daylight as possible; that is, to require white light. The problem, then, is to find a vapor which gives spectrum lines over the whole visible range, distributed approximately in the same manner as the intensity in the solar spectrum, and giving as few lines as possible outside of the visible spectrum.

A substance giving spectrum lines uniformly distributed in their intensity over the whole visible range, should not give white, but a pronounced green light, due to the higher physiological effect of the radiations in the middle of the spectrum. By the law of probability, amongst the spectra of the chemical elements, the predominant energy of radiation should be found just as often in one wave-length as in any other. Physiologically, therefore, green should predominate in the colors of metal spectra. To a certain extent this is true. Red metal spectra are rare, green most prominent. Bluish metal spectra, however, are much more frequent than should be expected by probability, and it therefore seems that in molecular vibrations of vapors, shorter wave-lengths or higher frequencies predominate. This may be due to the size and mass of the molecules being such as to have a mean frequency of oscillation higher than the average frequency of visible light.

V. VACUUM-TUBE ILLUMINATION.

Conduction through vapors can be of two distinctly different characters: spark or Geissler tube conduction, and arc conduction.

Vapors or gases can be divided into two classes: conducting vapors, and non-conducting vapors. The conducting vapors are all of very high resistance. Hydrogen or air may be called a conducting gas, because a current can be passed through it, especially at a moderately high vacuum, as in the Geissler tube, which is nothing more than a tube containing the gas used as a conductor, at a few millimetres pressure. At this pressure, air becomes a fairly good conductor, but the resistance is very high compared with the resistance of conducting solids or liquid. The passage of current through the conducting gas of the Geissler tube produces light, by some form of luminescence.

The mechanism of this light production does not seem to be known, but the light seems to be somewhat of the character of a by-product. The Geissler tube is extremely efficient when operated with an alternating current of very high frequency. With decrease of frequency, its efficiency decreases and heat is produced; that is, the frequency of radiation from the Geissler tube seems to vary with the frequency of the impressed alternating electromotive force, and have its intensity maximum near the visible range only at very high frequency currents. The production of light in the Geissler tube therefore seems to be connected in some way with the change of electric stress. It is not dependent on it, because even with a steady current the Geissler tube gives light, but its efficiency of light production vastly increases, and the energy is converted more into light and less into heat, with increasing frequency. Herein seems to lie the great difficulty in this method of producing light by using conducting gases at low pressure.

Considerable work has been done in this direction by able investigators, and with some success. The Geissler tube gives a very nice light; and by using a suitable gas it can be made to give any color, only the intrinsic brilliancy is very low. Very large tube surfaces must therefore be used for illumination, of a magnitude probably a hundred times as large as with the mercury arc, which latter is already recognized as a luminous source of low intrinsic brilliancy. In the last years, even with a frequency of 60 cycles, good efficiencies seem to have been reached. I do not believe it possible, however, to approach the magnitude of efficiency as given by the mercury, calcium, or titanium spectrum.

VI. THE ARC.

In the Geissler tube the current is carried by the gas or vapor which fills the space between the electrodes. The conduction is disruptive in character, or a spark discharge; that is, a minimum voltage is required. Below this voltage, no conduction takes place; above it the current passes, with the appearance of luminescence; and if the voltage falls below the minimum value required to start conduction, the current again ceases. The material of the electrodes has no direct effect, but the spectrum is that of the gas between the electrodes. The character of the current also seems to have no direct effect; alternating current passes at about the same voltage as direct current.

An entirely different set of phenomena is met in arc conduction. The electric arc makes its own conductor. That is, the current is carried across the gap between the electrodes by a vapor-bridge, produced by the current from the material of the negative electrode and maintained by the current as a high-velocity vapor-stream issuing from the negative towards the positive, and more or less surrounding the positive terminal. The spectrum of the arc, therefore, is that of the negative terminal, but independent of the gas or vapor filling the space around it, or of the material of the positive terminal, except indirectly by the effect of heat, etc.

The continuous production of the vapor-stream requires power in raising the negative material to the boiling point, evaporating it, and producing its rectilinear velocity. This power must be supplied by the electric circuit, as a potential drop at the arc terminals, independent of the length of the arc, and of the current—if the volume of the vapor-stream is assumed as proportional to the current, which seems to be the case. This potential drop, e_0, may be called the counter electromotive force of the arc.

The temperature of the arc-stream, at constant pressure in the surrounding space, must be constant, that of the boiling point of the material of the negative terminal. The power radiated per unit surface may therefore be also assumed as constant, and the total power radiated, and therefore the power consumed in the arc stream, as proportional to its surface; that is, to the product of length by diameter. Since the section of the arc-stream can be assumed as proportional to the current, it follows that the voltage consumed by the arc-stream is inversely proportional to the square root of the current, and approximately proportional to the arc-length, or, when allowing for the abstraction of energy from the arc-stream by the terminals, proportional to the arc-length plus a small constant quantity.

This gives the theoretical volt-ampere equation of the arc:

$$e = e_0 + \frac{a\,(l+c)}{\sqrt{i}}$$

Giving the arc length 1 in inches, numerical values of this equation are:

Carbon Arc:

$$e_0 = 36 + \frac{130\ (1+0.33)}{\sqrt{i}}$$

Magnetite Arc:

$$e_0 = 30 + \frac{123\ (1+0.05)}{\sqrt{i}}$$

With zinc or cadmium the counter electromotive force of the arc is:

$$e_0 = 16 \text{ volts,}$$

with mercury,

$$e_0 = 13 \text{ volts.}$$

In Figs. 2 and 3 are given characteristic curves for these arcs, for 2, 4, 8, 16 amperes, drawn from above equations with the values observed by test marked by crosses. As seen, the agreement of the calculated curves with test is as close as can be expected from an approximate formula, with the exception of the carbon arc, in which the agreement is least close. In the carbon arc, for short arc-lengths the curves leave the straight lines and slope down toward a value of about 28 volts at zero arc-length. Separating two carbon electrodes from each other and observing the voltage at the moment when the carbons leave immediate contact with each other and the voltage suddenly rises, or observing the voltage immediately before the carbons, when shortening the arc, come in contact and the voltage suddenly drops, also gives values around 28 volts. This, in connection with the high value of the constant $c = 0.33''$, looks as if in the carbon arc the seat of the counter electromotive force e_0 is not the immediate surface of the terminals, but a part of e_0, about 8 volts, resides in the space surrounding the electrodes. This phenomenon may, however, be explained also by energy transfer from the hot crater of the positive terminal to the negative terminal at a short arc-length.

For very low currents, where the arc-stream gets very thin and unsteady, and abnormally high energy losses may be expected, the above equations give small values; that is, the observed arc-voltage is higher than the calculated, especially with long arcs. So for the magnetite arc of one ampere, we find:

At arc-length	⅛ in.	½ in.	1 in.
Observed voltage	58	108	184
Calculated voltage	51.5	97.5	159

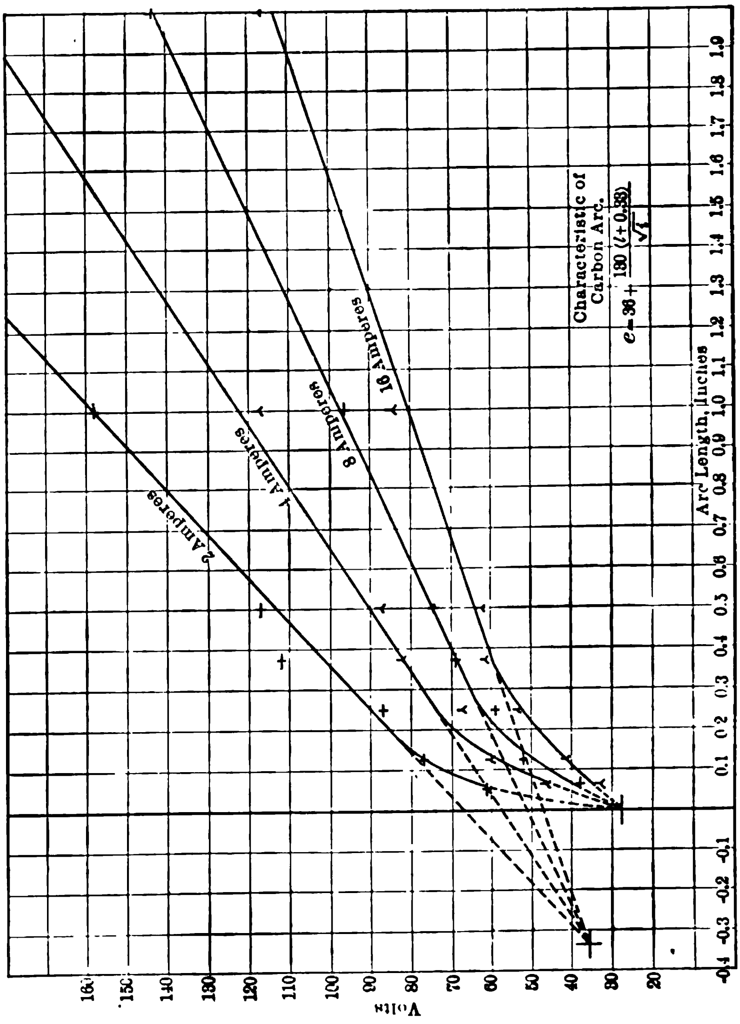

FIG. 2.

These equations obviously apply to the arc at constant pressure, as an arc in air, in which the arc-section varies with the current. For an arc of constant section, in which therefore the pressure and the temperature varies with the current, as the mercury arc in a vacuum, by similar considerations an approximate volt-ampere characteristic is found. This is for the mercury arc:

$$e = 13 + \frac{1}{1.68\,d - 0.066\,i - \dfrac{1.3\,d^2}{i}}$$

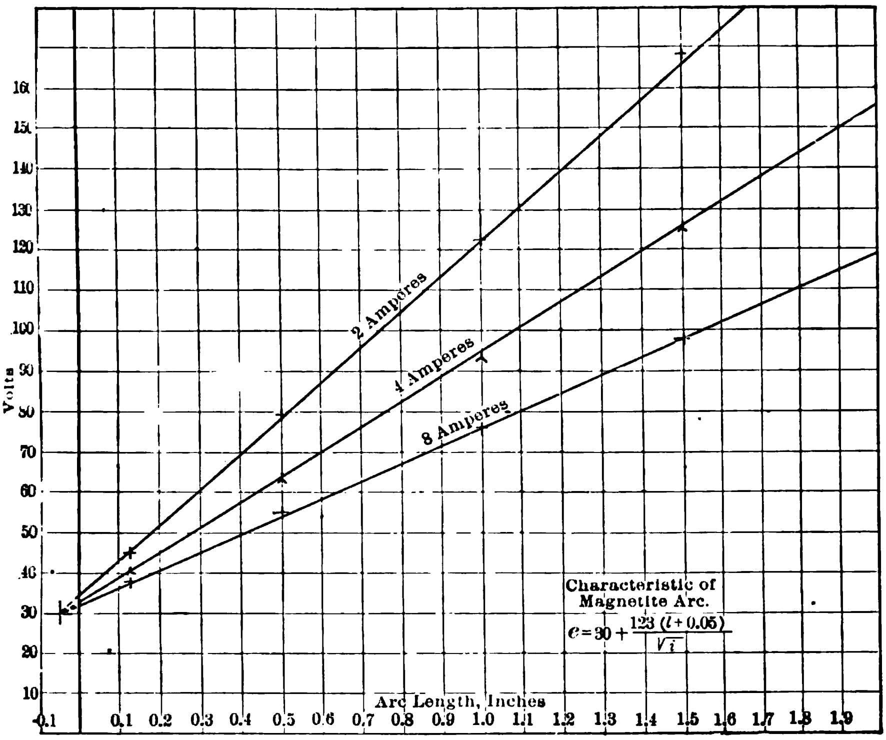

FIG. 3.

with non-volatile positive terminal, and:

$$e = 13 + \frac{1}{1.68\,d - 0.114\,i - \dfrac{1.3\,d^2}{i}}$$

with mercury anode,*

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* The effect of the anode material on the arc characteristic is indirect. In the case of the mercury anode the heat produced at the anode causes evaporation, and increases the vapor pressure above that existing with a graphite or iron anode.

where: 1 = arc-length,
d = arc-diameter, in inches.

From the character of arc-conduction—that the current makes its own conductor—it follows that the arc must be started; that is, the vapor-bridge which carries the current must first be produced by the expenditure of energy, before the current can flow. This can be done in many ways: by bringing the terminals in contact with each other and so starting the current, and then by withdrawing the terminals from each other to form the arc-stream by the current; or by jumping an electrostatic spark across the gap and so starting conduction.

It also follows that the arc is a direct-current phenomenon, and in general can not exist with an alternating current. With an alternating electromotive force, at the end of the half-wave the current dies out and therefore also the vapor-stream; and the next half-wave, to pass in opposite direction, requires a vapor-stream moving in the opposite direction. This does not exist, and the current does not pass; but the arc dies out at the end of the half-wave, except if the supply voltage is sufficiently high to jump a spark across the terminals at every half-wave, through the residual vapor left by the preceding half-wave. An alternating arc, therefore, must be at every half wave in the condition of starting by a spark. Stroboscopic photographs with metal arcs show this phenomenon: a sharply defined static spark at every half wave, gradually spreading out to the more diffuse arc-flame and then dying out at the end of the half-wave, to start again by a spark at the next half-wave.

The voltage required to maintain the vapor-stream; that is, the voltage consumed by a direct-current arc, as discussed above, increases with increase of the arc-temperature; that i., increase of the boiling point of the terminal material. It is lowest for the mercury arc, highest for the carbon arc. For a ½-in. arc it is shown approximately by Curve I in Fig. 4, with the temperature as abscissas. The voltage required to jump a spark across the gap between terminals, shown roughly by Curve II in Fig. 4,* decreases with increasing temperature, as is well known, and intersects Curve I at some temperature, A, probably somewhere between 2500° and 3000° cent. Above this tem-

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* This curve is only estimated, and so can make no claim to numerical accuracy. Curves I and II, the arc- and the spark-curve, are shown once more in ⅕ scale (left-side ordinates) in dotted lines as I′ and II′, and the lower part of II once more, in $\frac{1}{25}$ scale, as II″ in Fig. 4.

perature, the spark-voltage is below the arc-voltage, and a voltage sufficiently high to maintain an arc is therefore sufficiently high to start it again at each half-wave of alternating electromotive force. That is, materials as arc terminals, which have

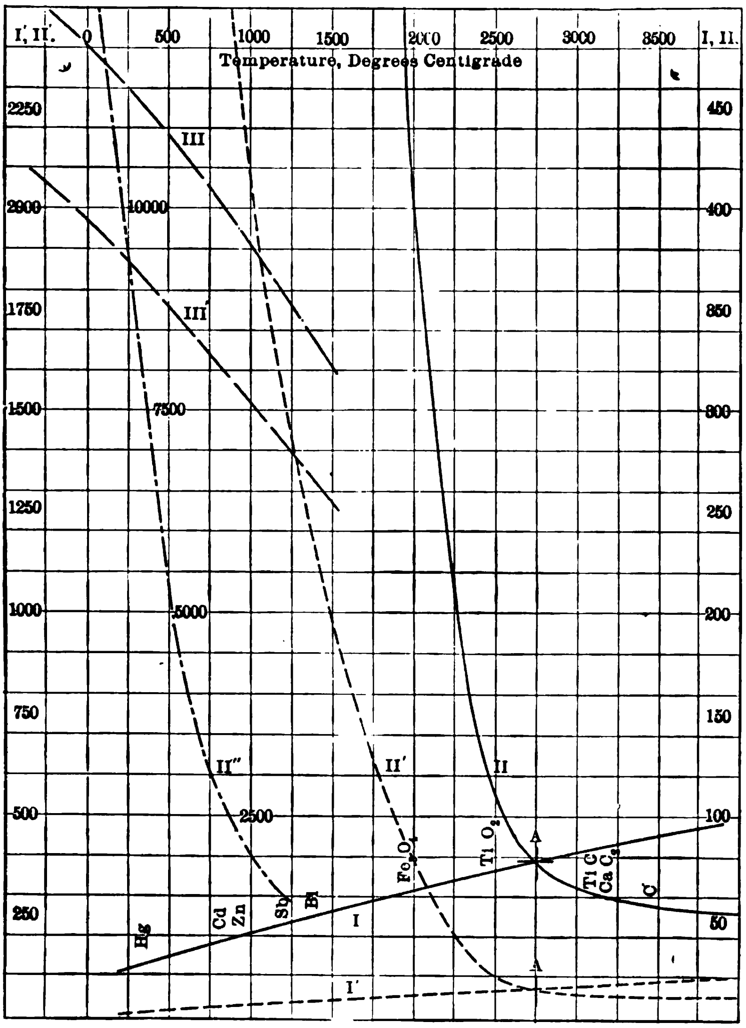

Fig. 4.

a boiling point above the temperature of intersection *A* of Fig. 4 maintain a steady alternating-current arc at about the same voltage as a direct-current arc; while materials with a lower boiling point than A require a higher voltage, usually very many times higher, to maintain an alternating, than a direct-current arc. It must be considered, however, that the temperature of the boiling point, while being the foremost factor, is not the only factor in determining the position of a material on Curves I and II, Fig. 4. Individual characteristics somewhat modify the position.

Where therefore spark-gap terminals are desired not to maintain an alternating arc, as for lightning-arrester cylinders, they are found on the lower range of the curve: mercury, cadmium, zinc, antimony, bismuth,—the so-called "non-arcing metals;" Where electrodes for alternating-current arc lighting are required, they are found at the upper end, above A. In this range belong carbon and most carbides, as those of calcium and titanium. Even carbon shows the phenomenon of restarting at every half-wave, by a high peak at the beginning of the electromotive force wave, as shown first by Tobey and Walbridge, in a paper on alternating-current arc waves.* With increasing approach to A, this peak at the beginning of the electromotive force increases in height, and the power-factor of the circuit tends to decrease, by wave-shape distortion. Immediately below the intersection point A are found very refractory metals as tungsten, and metaloxides, as those of titanium, etc.

The range of voltage between Curves I and II in Fig. 4 is the range in which rectification takes place. That is, by maintaining the vapor-stream issuing continuously from one terminal, by an outside source, or by the overlap of several arcs, the alternating electromotive force can pass a current in one direction only, and so is rectified. In this range, the arc-stream is a unidirectional conductor, of very low resistance in one direction, of practically infinite resistance in the opposite direction.

The voltage range of rectification, then, is highest at the lower end of the curve, and decreases gradually to zero at the point A. With the first members of the group, the upper limit of the rectification range is somewhat cut down, by the disruptive strength of the air surrounding the arc-stream being lower than that of the arc-stream, and so passing a static spark outside of the arc-stream, or, with a vacuum-tube arc, by a Geissler tube discharge through the residual gas. In the latter case the maximum voltage which can be rectified depends upon, and measures the

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* Transactions A. I. E. E., 1890, Vol. 7, p. 367.

perfection of evacuation. Such Geissler tube discharge curves are sketched roughly, in dotted lines, as III, III[1] in Fig. 4.

While vapors like mercury, zinc, etc., are very good conductors when in motion under the influence of the current, of a conductivity comparable with that of electrolytes; when not under the influence of the current they are almost perfect insulators, and so can be distinguished from the so-called "conducting gases," as hydrogen, air, etc., as "non-conducting vapors." Low-temperature metal vapors thus are non-conductors.

VII. THE ARC AS AN ILLUMINANT.

The spectrum of the arc is that of the negative material; its temperature that of the boiling point of the negative. There are, however, some apparent exceptions. For instance, the arc-stream can be superheated by using a high-frequency oscillating current of sufficiently high voltage to maintain an alternating arc, and a frequency so high that a sufficient vapor-stream can not be formed during the half-wave. In this case, groups of spectrum lines frequently become prominent, which are insignificant with saturated vapor: the mercury arc becomes bright-red in color; the iron arc loses most of its brilliancy, but gives a great quantity of intense ultraviolet rays, etc.

Likewise, the spectrum of the positive, or a constituent of the positive terminal, can be made to appear in the arc. The tip of the positive is heated to the temperature of the vapor-stream, in the carbon arc the temperature of boiling carbon. If the positive terminal consists of, or contains some material which boils below the temperature of the vapor-stream, then it will evaporate out of the positive, and may thus enter the arc-stream. For instance, in a carbon arc, or arc with carbon as negative, if a carbon is used as positive, impregnated with calcium fluoride or borate, which has a relatively low boiling point, then the calcium vapor enters the arc-stream and is thereby heated to the temperature of the carbon arc. It becomes luminescent, whether directly by heat, or indirectly by chemical dissociation, or otherwise, need not be considered here. So the efficiency of a carbon arc can be increased by feeding into the arc-flame the vapor of some material which gives a brilliant spectrum—as calcium, which gives a yellow light of very great brilliancy. It is fed into the arc by the positive terminal, because this is the hottest, and the efficiency depends entirely on the temperature of the positive. If the positive is very large, so as to keep cool and consume slowly, the efficiency decreases, because it is produced only indirectly by material being evaporated from the positive and then as vapor entering the arc-stream. Therefore a high temperature and rapid consumption of the positive are necessary.

It is entirely different with the true luminous arc, which carries the light-giving material into the arc-flame by the electric current, as the vapor-blast, which carries the current. The carbon as negative material is objectionable, since it gives the non-luminous carbon arc. Iron appears to be a very suitable material, since it gives a spectrum extending over the whole visible range. It produces practically a white light. The positive can then be maintained cold without affecting the brilliancy or efficiency of the arc. The negative can also be cooled without appreciable effect on the efficiency, since the current still produces the vapor-blast from it, and so the light. If cooled too much the voltage in the arc may rise a little, because it requires more energy to produce the iron vapor from the cool negative than from the hot negative, but still the efficiency is not much affected.

There are, then, two distinct ways of producing luminescence of the arc: first, directly by using some material as negative which gives a luminous spectrum; that is, a spectrum with many lines in the visible range, preferably covering this whole range, to get white light; secondly, indirectly by using some material to carry the current which gives a very high temperature to the arc-stream—which means practically carbon—and making the arc-stream luminous by feeding some light-giving substance into the arc from the positive terminal. In the former case the arc has the characteristic of the iron arc or titanium arc, whatever material is used; in the latter case, it has the characteristic of the carbon arc.

Since the carbon arc is the steadiest arc, the most work has been done in the latter direction. The former method, of feeding the luminescent material by the current from the negative material, has the advantage, however, that the efficiency does not depend on the temperature of the electrodes: the rate of consumption of the negative electrode can thus be greatly decreased by maintaining it at low temperature; while the positive electrode, which takes no part in the arc conduction, can be made entirely non-consuming. This method seems to be a more direct conversion of electric power into light.

These two forms of arc have come into prominence recently; the flame carbon arc and the metal compound arc; that is, an arc in which carbon is not used, but some other material which gives a luminous spectrum, as iron or titanium. In the former case the characteristics are those of the carbon arc. All the materials which can be used to increase the efficiency of the carbon arc—calcium compounds are used almost exclusively—deposit as solids after passing through the arc-flame, and therefore ventilation must be provided to carry off the smoke; that is, the arc must be a so-called "open" or "short-burning" arc. The life of the electrodes is about 10 hours. Flame carbon arcs therefore have short life of electrodes, though their efficiency is high. Again, efficiency has to be balanced against life, or decreased cost of power against increased cost of electrodes and attendance. Here in the States the short-burning arcs for street lighting have practically disappeared. Indoors the excessive brilliancy and the smoke are objectionable, so that the flame carbon arc does not offer much prospect for general illumination.

More prospect of success appears to exist in the true luminous arc, an arc using as negative a material giving an efficient and brilliant spectrum. Such material should give lines uniformly distributed not only in the green or yellow, but over the whole visible range, and the material should not be attacked in air, even at high temperature. The arc must be an open arc, since the material deposits as solid, and to get electrodes with long life, a material is required which is stable at high temperature in the air.

There are very many metals which give luminous spectra, but those which give white are substantially the metals of the iron group only—iron, titanium, wolfram, etc.

Long-burning quality requires a material which is not affected, or only little affected by the air. This, in general, excludes the metals, but requires a stable oxide or other fairly stable compound, as some carbides are. It should also be a conductor, since as arc electrode it has to carry the current. In the intermediate oxide of iron, magnetite ($Fe_3\,O_4$), a material is found which is a good conductor, is stable at high temperatures as well as at low temperatures and gives a white spectrum. In such an electro luminescent arc, any stable material is suitable as a positive terminal. Copper is generally used because it is cheap, is stable at fairly high temperature, is a very good conductor of heat, and when heated by the arc carries the heat away with sufficient rapidity not to melt or oxidize appreciably. In all these arcs the vapor stream from the negative is a necessity. In the mercury arc it is easiest of observation, because the arc is enclosed in a glass tube.

The amount of vapor produced by the current from the negative is usually many times greater than necessary to carry the current, and most of it can be condensed without any appreciable change in the arc-stream. So also magnetite consumes at a much greater rate than is necessary, of an order of ½ gram per-ampere-hour. This rate of evaporation is greatly reduced by the addition of small quantities of a material which is chemically not much different from magnetite, but is much more refractory; so that at the temperature where the magnetite melts this material is still solid and forms a kind of sponge in which the melted magnetite is held and its consumption greatly retarded.

Magnetite, however, while a good conductor of the arc-stream, is not very efficient as a producer of light, and added thereto are other materials which give a very high efficiency, as titanium compounds.

In the magnetite arc—as used at present, that is, in which the magnetite electrode contains titanium oxide, etc.—magnetite is essentially the carrier of the arc conduction, just as carbon in the yellow-flame arc; titanium with its highly efficient white spectrum takes in the magnetite arc the same place as calcium in the flame arc, as light-giving substance, but titanium is carried into the arc stream by the current from the negative, while calcium in the flame arc enters by evaporation from the positive.

The elimination of carbon in the magnetite arc excludes combustion, and this increases the life of electrodes to about twenty times that of carbon electrodes under the same conditions; but just as with the carbon arc, the efficiency of the magnetite arc can be varied over a wide range, with a corresponding variation of life in opposite direction. That is, by sacrificing some efficiency the life can be greatly increased, or the efficiency can be increased by somewhat reducing the life, by increasing the percentage of light-giving material: usually titanium oxide in the magnetite arc, calcium fluoride or borate in the flame carbon arc. In either case, a very high percentage of the light giving material tends to the formation of a non-conducting slag at the electrode surface, and if the highest possible efficiencies are desired—½ watt per candle-power, and better—the effect of the non.conducting, or poorly-conducting electrode surface has to be eliminated, by starting the arc from the side of the electrode, or some other method.

Magnetite, titanium oxide, and most metals or their compounds are on curve Fig. 4 below the intersection point A; that is, do not maintain a steady alternating arc. For alternating arcs, therefore, one of the materials is required which is above point A in Fig. 4. In this range, there are carbon, carbides, and similar compounds.

Thus the titanium arc with alternating current can not use magnetite as carrier, and titanium oxide as light-giving material; but titanium carbide is used as arc conductor. It obviously is not so incombustible as the oxide, but still so much more stable than carbon as to be well within the range of long-burning arcs.

To conclude, then, in the luminous arc we seem to have the first instance of a commercial application of a direct conversion of electric power into light, without heat as intermediary form of energy. It is not limited to very low values of efficiency. But so far it seems that only the green mercury spectrum, the yellow calcium spectrum, and the white titanium spectrum offer an efficiency so vastly superior to that of incandescent solids, that as regards the efficiency of light production no possible improvement in incandescent lighting could hope to approach it. Typical of these three most efficient spectra are the mercury-arc lamp, of practically infinite life and bluish-green color of light; the yellow flame carbon arc of the short life of the open arc-lamp of old; and the white titanium carbide or magnetite arc, of a life equal to or greater than that of the enclosed carbon arc.

A paper presented at the 211th Meeting of the American Institute of Electrical Engineers, New York, Nov. 23, 1906.

NEW TYPES OF INCANDESCENT LAMPS.

BY CLAYTON H. SHARP.

For a number of years the standard of electric lighting has been set by the carbon-filament lamp consuming initially 3.1-watts per candle-power. Progress there has been; but it has been chiefly in the way of minor improvements in the process of manufacture, rating of lamps, and in the way of a more general adoption by electric lighting companies of the 3.1 watts-per-candle lamp. This watt-per-candle consumption has been recognized as the minimum practicable under good operating conditions. Any radical or considerable improvement in the lamp itself has seemed improbable of attainment. The degree of improvement which has been made in the carbon filament lamp has been indicated by data given by Mr. J. T. Marshall in a paper before the Franklin Institute*. The continuous increase in the effective life of incandescent lamps burned at 3.1-watts per candle between the years 1888 and 1904, as given in Marshall's paper, are shown in the curve, Fig. 1. The effective life at the present time is seen to be substantially two and one half times as great as the life in 1888. The advent of the osmium lamp cannot be said to have altered the state of affairs materially. In spite of its very high efficiency and long life, this lamp seems precluded from exercising any revolutionary influence on lighting practice, on account of its low voltage and most of all by the limitations of of the visible supply of the material of which the filament is composed.

Within the last two years the situation has altered materially. A marked improvement in the process of manufacture of carbon-

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Journal of the Franklin Institute, 1905, vol. CLX, p. 21, filament lamps which has been announced and described by Mr. John W. Howell before this Institute has resulted in the commercial production of lamps which operate on a 2.5-watts-per-candle basis instead of a 3.1-watts-per-candle basis.

A German firm, going back to the class of materials employed in the earliest attempt at the manufacture of incandescent electric lamps, has produced a lamp with a wire of tantalum as the glowing body and with an efficiency greatly in advance of that of the established carbon filament. More recently still, various experimenters have succeeded in producing lamps with a filament of metallic tungsten which carry the standard of efficiency to a point far beyond that obtainable with either carbon or tantalum. Since the graphitized or " metallized " carbon filament has in this country become a regular commercial product, the properties of which are moderately well known, it is deemed best in this paper to take up more in detail the peculiarities or the properties of the tantalum and the tungsten lamps.

PROCESSES OF MANUFACTURE.

It is not necessary in this place to go into a discussion of the processes of manufacture of the filaments of the metallized carbon and of the tantalum lamp, nor of the appearance of the lamps themselves, since these have become quite well known. In the case of the tungsten lamp, certain peculiarities of the construction are made necessary by the properties of the tungsten filament itself. The metal tungsten (German " wolfram ") while ordinarily reckoned as one of the rare elements, yet is from the point of view of lamp manufacture quite plentiful enough for all practical purposes. While its price per pound is high, yet considering the weight of the metal entering into an incandescent lamp, it is not especially expensive. One of its most important uses at the present time is the production of tungsten steel. The metal is infusible by any ordinary process. The melting point of tungsten filaments has recently been given by Waidner and Burgess† at 3200° cent. The metal is commercially obtainable in the form of a fine powder. Tungsten does not seem to be ductile, so it is impossible to draw it directly into a fine wire, as is done successfully in the manufacture of the tantalum filament. Tungsten unites readily with oxygen and with carbon at high temperatures. These peculiarities have

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*Asheville Convention paper, 1905.

†Electrical World, 1906, vol. XLVIII, p. 915.

made the problem of the production of tungsten filaments a rather difficult one. It has been attacked from several sides, and different processes for the manufacture of tungsten filaments have resulted therefrom.

The earliest process to be brought to public attention was that of Dr. Kuzel. Kuzel's process consists in the production of a colloidal solution of tungsten by forming an arc between terminals of the metal under the surface of water. The colloidal solution, when it has been brought to the proper consistency is squirted through a die into filaments, which after being dried are converted from the colloidal condition into the crystalline condition by the passage of an electric current through them. In this way the filament is produced without introducing any carbon, which would unite with the tungsten to form tungsten carbide, a compound which is readily formed and which is very detrimental to the quality of tungsten filaments.

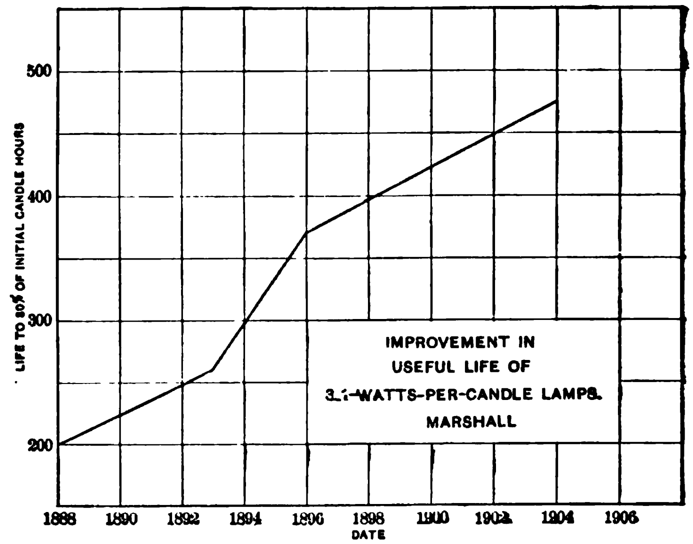

Fig. 1.

Another process is the substitution process of Dr. Just and Hanaman. This process seems to be very similar to one patented by Lodyguine some ten years ago. In this process a very fine carbon filament is heated in an atmosphere of a chloride of tungsten and hydrogen. Under proper conditions of the experiment, tungsten is deposited upon the carbon filament, the hydrogen acting as a reducing agent. By heating the filaments by means of a current the whole filament is converted into tungsten carbide. The carbon made is then removed from the filament by heating the same in an atmosphere of steam and hydrogen. The steam is decomposed, its oxygen uniting chiefly with the carbon of the carbide. Whatever tungsten is oxidized in this process is reduced again by the hydrogen which is present. It is impossible to say exactly whether this process is actually used in the manufacture of these lamps or not, though the statement may be made with a reasonable degree of certainity that some substitution process is used by Dr. Just and Hanaman.

The manufacture of filaments of osmium presented a problem similar to that of the tungsten filament. It is, therefore, natural that the process of Dr. Auer von Welsbach should by proper modification be adapted to the manufacture of tungsten lamps. Experiments along this line have been carried on by the companies in Germany and Austria which have been engaged in producing osmium lamps. To the tungsten lamp manufactured by the Osmium Lamp Company of Vienna has been given the name of the Osmin lamp. The tungsten lamp of the Auer Company of Berlin is called the Osram lamp. While it is reasonably certain that the details of the processes of manufacture of these two lamps differ from each other, yet they are probably alike in their general features. The method consists in forming a paste of finely-divided tungsten with a binder of organic material such as, for instance, sugar solution, and squirting the same into filaments through a die. The carbon is then removed from the filaments by heating the latter in an atmosphere of steam and hydrogen or by the use of some similar process.

Still another tungsten lamp is known as the "Z" lamp. The process by which it is manufactured involves also a squirting of a paste consisting of finely divided tungsten with an organic binder, but differs from the other in the method employed to remove the carbon.

A well-known manufacturing company in this country has announced* that it is about to put a tungsten lamp upon the market, made by a process differing from all those mentioned above, but no information as to the nature of this process is available.

It has also been annonuced that Mr. John A. Heany has been

**Electrical World*, Vol. XLVIII, p. 319.

successful in producing tungsten lamps, but details as to his method of operation are also entirely lacking. Some lamps made by Mr. Heany have been the subjects of experiments made at the National Bureau of Standards.*

It will be seen from the foregoing that the possible methods for producing tungsten lamps are probably quite numerous, and that the prospects are that we shall have in the near future a number of competing processes of varying degrees of merit. Time and experience will be required to show which is best adapted to practical application.

PHYSICAL CHARACTERISTICS.

Tungsten lamp filaments manifest all the ordinary properties of wires of pure metals. They have high conductivity and a large positive temperature coefficient. The high conductivity of the material requires that the filaments shall be very fine and quite long if they are to be used in producing lamps giving a reasonably low candle-power on 110-volt circuits. The degree of fineness to which it has been possible to reduce these filaments is indicated by the following table:

		Diameter
Tantalum,	110 volt, 22 c-p	0.052 mm.
Osmium,	16 volt	0.103 "
Z	New	0.1 "
	After burning	0.055 "
Osram,	After burning	0.044 "

A fine hair may have a diameter of about 0.06 mm. In view of the extraordinary degree of fineness which has already been attained in the manufacture of these filaments it does not seem probable that very much more can be looked for in this direction.

Tungsten filaments, when at the temperature of full incandescence, are quite soft. It is, therefore, not feasible to produce them and mount them in lamps in any other form than in loops. The result is that the tungsten lamp takes on the appearance shown in Fig. 2, which illustrates a 110-volt Osram lamp. In this lamp it will be seen that the filament consists of four loops. The ends of each loop are attached by means of a paste or by actually fusing them fast by the use of an electric arc to wires brought out from the stem of the lamp. The stem of the lamp is prolonged and carries at its lower extremity wires which serve

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**Electrical World*, loc. cit.

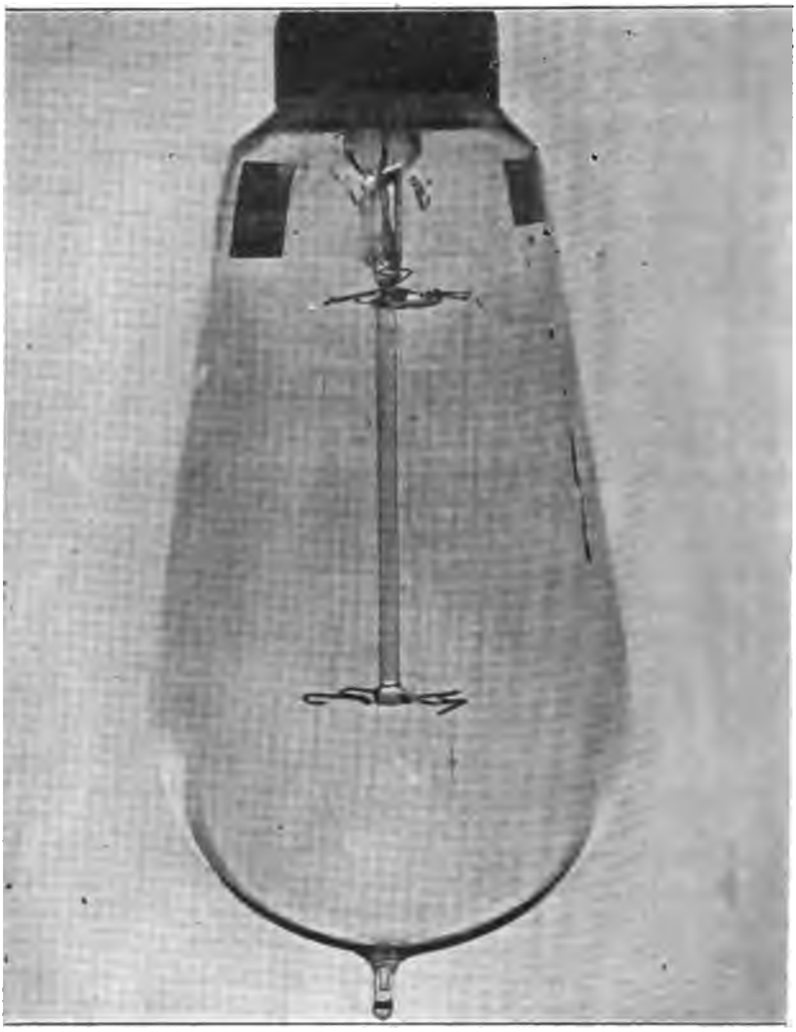


FIG 2.

as guides and supports for the loops of the filament. All the lamps which have been exhibited up to the present time have been intended for burning only in a pendant position. It can be stated, however, that by certain modifications in the details of construction lamps are now being made which can be burned in any position. The first tungsten lamps produced were designed for low voltages. In consideration of the high conductivity of the material, the production of a low-voltage lamp is a more simple problem than the production of one of higher voltage, since for low voltages a shorter length of the filament may be employed. It would seem also that it is easier to produce a lamp of high candle-power than of low candle-power, since a stouter filament may be employed in the high candle-power lamp.

As far as the writer knows, no 110-volt lamps have been produced as yet for lower candle-powers than 25 and no lamps have been produced for higher voltages than 220. The fineness of the 110-volt, 125 candle-power filament is such that it would seem to be difficult to produce such a lamp as a regular commercial article. The 220-volt lamps are probably only experimental as yet. The properties of the tungsten filament is such that it would seem to lend itself very readily to the production of most excellent lamps for street lighting by the series incandescent system. Lamps for 110 volts are likely to have when commercially produced a watt consumption of 50 watts or more. If tungsten lamps are to be made for small candle-powers, such as are commonly employed in domestic lighting, they would probably need to be made for 50 volts or under, and consequently either burned in series or connected to low-voltage mains.

One of the chief disadvantages of the tungsten lamp lies in the extreme fragility of its filament. Blows or shocks given to the lamp are quite likely to cause a rupture of the filament. A ruptured filament may, however, mend itself by the parts welding together once more, but where the filament has become welded it is quite likely to break loose again.

ELECTRICAL CHARACTERISTICS.

The feature which differentiates the electrical behavior of the newer lamps from the ordinary carbon lamp is their positive temperature coefficient. The temperature coefficient of the ordinary treated carbon filament has been shown by Mr. John W. Howell to be very nearly zero at the temperature of ordinary incandescence. At lower temperatures its coefficient is negative. The term "metallized" has been given to the carbon filaments treated by the high-temperature process on account of the fact that these filaments at their temperature of incandescence have a positive coefficient. The tungsten and tantalum filaments have also positive coefficients which are, moreover, much larger than the positive coefficient of the "metallized" carbon. The temperature coefficients of tantalum, osmium, and tungsten filaments have been determined by measuring the resistance of these filaments at room temperature and again at 100 degrees centigrade. The coefficients as found were as follows:—

Tantalum	0.234	per cent. per degree
Osmium	0.372	" " " "
Tungsten (Osram lamp)	0.438	" " " "

It will be noted that the temperature coefficient of the osmium filament corresponds very closely to the temperature coefficient of pure platinum. The temperature coefficient of the tungsten lamp is higher and that of the tantalum filament is lower than the average coefficient for pure metals. In accordance with the general law that the presence of impurities reduces the temperature coefficient to a very marked degree, it would appear that the tungsten of the Osram lamp was very pure, while the tantalum of the tantalum lamp either contained some slight trace of impurity or that the metal was in such a condition, due possibly to crystallization or to lack of annealing that its coefficient was abnormally low.

The effect of the positive coefficient is to give the metal-filament lamps considerable inherent regulation. That is, the change of current through the lamp is no longer proportional to the change in voltage, but is smaller proportionally than the change in voltage. Consequently in watts, candle-power, and watts per candle these lamps undergo smaller changes with the change in the line voltage than is the case of the carbon-filament lamp. These characteristics are brought out in the curves of Fig. 3. From the data used in plotting the above curves the following table has been taken which shows the change in candle-power and in the watts per candle of carbon, metallized, tantalum, and tungsten lamps with 5 per cent. rise in the voltage.

TABLE III.

CHANGE WITH 5 PER CENT. INCREASE IN VOLTAGE ABOVE NORMAL.

	Candle-power	Watts per Candle
Carbon	+30%	—15%
Metallized	+27%	—13%
Tantalum	+22%	—11%
Tungsten	+20%	—10%

The quality of the lamps here pointed out is a very valuable one since it must have two important results:

1. The light of the lamps is less affected by bad regulation of the circuit. This means that with a given degree of regulation of the voltage on the circuit, the service must be more satisfactory to the user, and has a direct bearing on the amount of copper required in feeders.

2. The life of these lamps is probably less affected by the momentary or even continued application of excessive voltages.

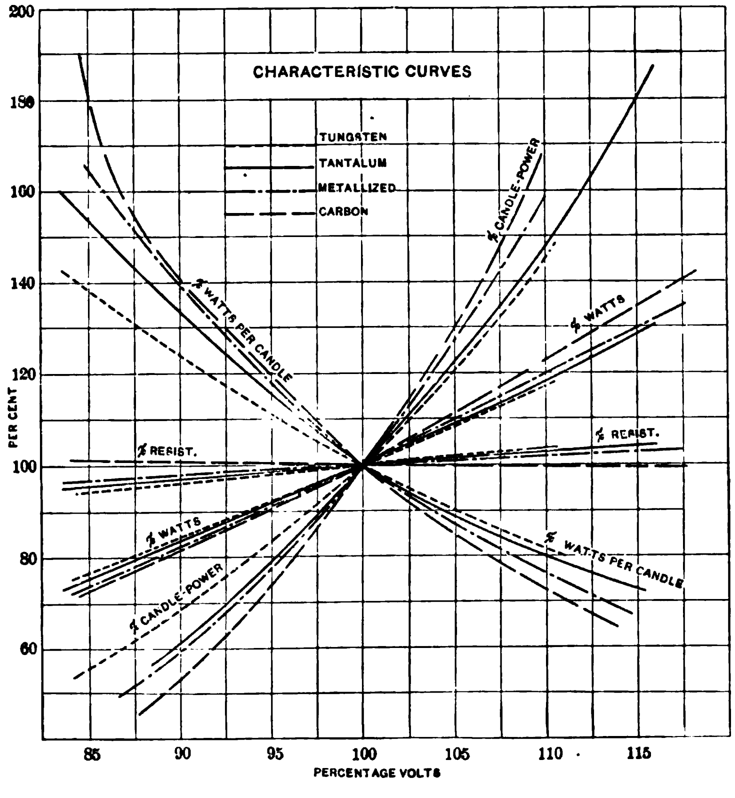


FIG 3.

Another interesting consequence of the positive temperature coefficient is that at the instant of closing the circuit the current through a metallic filament is much greater than it is a fraction of a second later when the current has had time to heat the filament to its normal temperature. In other words, there is an initial inrush of current similar to that experienced in an arc lamp or in a motor, but enduring for a much smaller period of time. The behavior of the ordinary carbon filament is the reverse of this. This effect is clearly shown in the oscillograph curves of Fig. 4, in which one record shows the initial current through a carbon filament and the other the initial current through a tantalum filament.

The position of the two spots of light before the circuit was closed is shown at the right of the figure. On closing the circuit, the instantaneous value of the current through the tantalum lamp is very high, but decreases with great rapidity. The instantaneous value of the current through the carbon filament is much lower, and gradually reaches its maximum value. The consequences of this can be perceived by the eye. Since the initial inrush into the metallized filament causes it to come to full incandescence much more quickly than does the carbon filament, the relative sluggishness of the carbon filament is readily appreciated by the eye when the metallic filament and the carbon filament lamp are lighted up side by side on the same circuit.

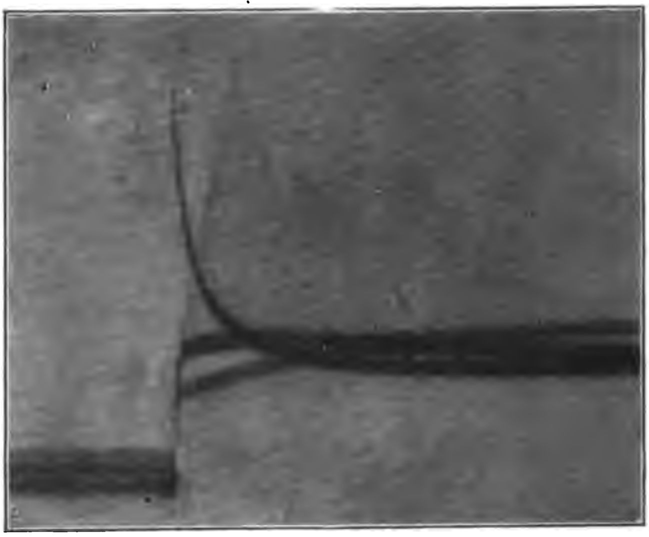


Fig. 4.

Distribution of Luminous Intensity.

The distribution of luminous intensity in the horizontal plane for both tantalum and tungsten lamps must be on the average a circle, due to the method of construction of the lamps. This circle contains in each case a number of narrow maxima which are due to reflections from the opposite side of the bulb. Curves of vertical distribution of a tungsten lamp and of a new and an old tantalum lamp are shown in Figs. 5 and 6. The difference between the curves of the old tantalum lamp and the new tantalum lamp brings out a marked peculiarity of the tantalum lamp when constructed with a straight-sided bulb. It points to a change in the spherical reduction factor or ratio of the mean spherical to the mean horizontal candle-power of the lamp during its life. Such a change is actually shown by the lamp. The change in vertical distribution may be traced to two causes; first, to the fact that during the course of the burning of the lamp a heavy deposit of black material is left on the bulb in a zone of a width substantially the same as the length of the spires of filament stretched between their support. This zone of blackening decreases strongly the horizontal intensity of the lamp, and

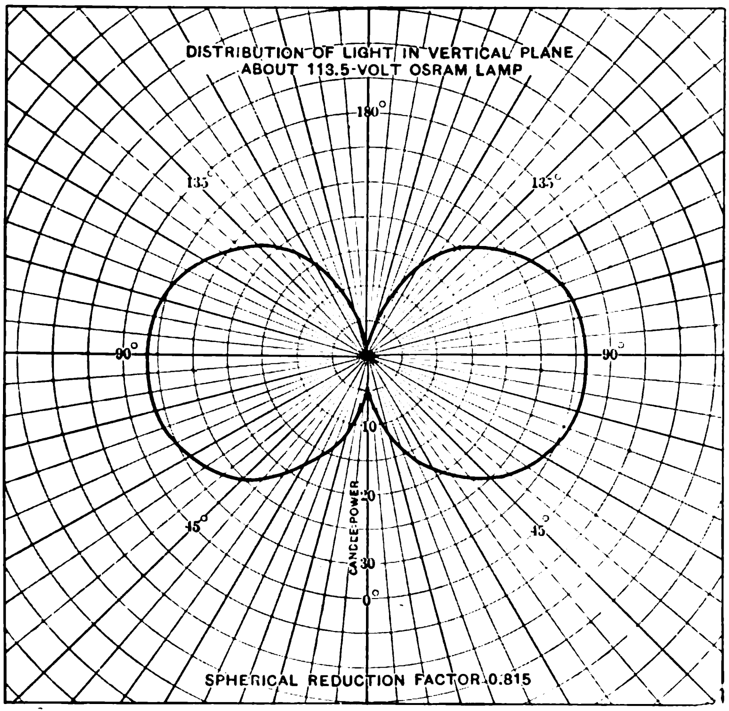


FIG. 5.

much less strongly the intensity in the direction of the tip. Hence, the candle-power as measured through the tip becomes relatively stronger as time goes on.

Another cause of this change is probably the increased roughness of the filament of the lamp. When the lamp is new, the filament appears as a fine smooth wire, looking like polished steel, and showing, under the microscope, a uniform surface, except for very slight pittings. A wire of this sort would radiate very little in directions nearly parallel with its length. The law which applies to a body having a perfectly black surface is that the radiation is proportional to the cosine of the angle of emission of the rays. The radiation from such a body as the tantalum filament would decrease more rapidly than according to this cosine law, consequently there would be a deficiency of light in directions not at right angles to the filament. The filament, however, becomes roughened with use, and the little projecting surfaces would tend to increase the radiation in these directions.

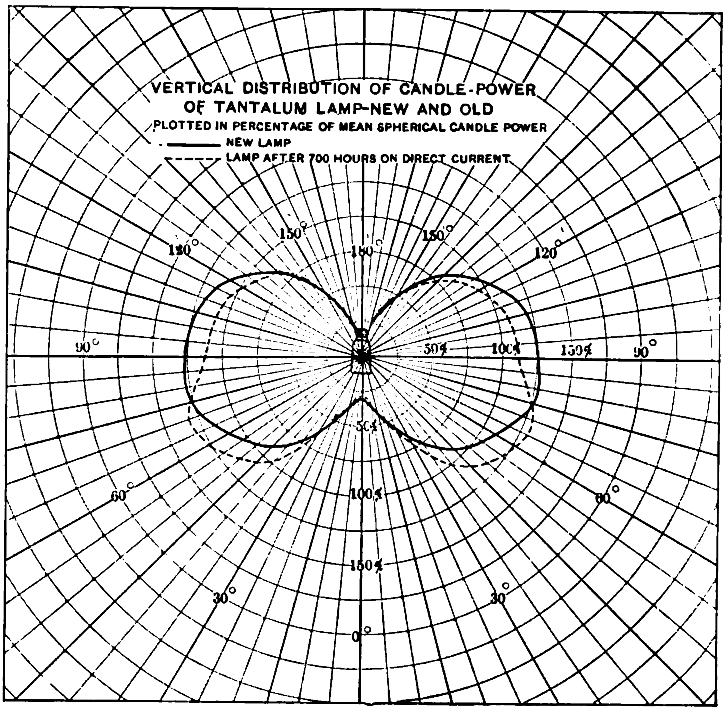


FIG. 6.

The spherical reduction factors for twenty tantulum lamps, as shown in Table V are extremely variable, falling as low as 0.69 and rising as high as 0.76. The cause for this is probably in the difference in the degree of polish of the surface of the filament. A lamp having a filament in the form of a straight cylindrical rod of perfectly black surface would show a theoretical reduction factor of 0.785. Practical carbon-filament lamps never have a factor smaller than this. A lamp of this character would give no light through the tip. The fact that the tantalum lamp shows smaller reduction factors than this value indicates how comparatively feeble is the radiation of this polished wire in other directions than normal to the surface. The value of this reduction factor shows, however, a very large increase during the life of the lamp, as is seen from the table, the change amounting, in some cases, to over 30 per cent. This is leaving out of consideration lamps which show an abnormal change in reduction factor, due to short circuits among the spires of the filament, These changes represent the combined influence of the roughening of the filament and of the deposit of the zone of black on the bulb so as to intercept the horizontal rays. An important conclusion from the facts here noted is that it is absolutely necessary, if we are to obtain any adequate idea of the performance of the tantalum lamp, to make measurements of the mean spherical rather than of the mean horizontal candle-power. Measurements of the horizontal candle-power alone, the spherical reduction factor being unknown, are likely to be misleading and fallacious. This is not the case with the carbon filament. in which the spherical reduction factor is quite a definite and unvarying quantity for a given type of filament.

"USEFUL" LIFE OF METAL-FILAMENT LAMP.

It has been customary to consider as the useful life of a carbon-filament lamp its life up to the time when its candle-power has fallen to 80 per cent. of its initial value. Beyond this point it has been considered cheaper to discard the old lamp and replace it with a new one; in other words, this has been taken to be the proper "smashing point" of the lamp. It should be pointed out that this relation does not hold with the metallic-filament lamps. The smashing point of a lamp is determined by considerations of initial cost of the lamp, the cost of electrical energy, and the rate of decline of the candle-power of the lamp. In the metallic filament lamps we have lamps of much higher economy, not only initially, but throughout their life; they are lamps of higher candle-power and necessarily of higher initial cost. It would seem that the data at present available regarding such lamps are not sufficient to permit of the proper determination of the smashing point. Certain it is, however, that where such lamps are used they are likely to be burned until they fail. This is the condition which is almost necessarily brought about by their relatively high cost.

A feature which marks both the tantalum and the tungsten lamp is the ability of the filaments sometimes to repair themselves after having been broken. If the broken end of a filament becomes crossed with another portion of the filament so that the electric circuit is completed the lamp once more lights up. In the case of the tantalum lamp, a junction of this kind may result in a very strong weld, so that a point of this sort does not necessarily constitute a point of especial weakness in the filament. Welds of this sort between tungsten filaments operated at normal voltages are much less secure and are quite liable to break apart. After a repair of this sort the candle-power of the lamps is usually higher than before, due to the decreased length of filament which the current must traverse. The occurrence of breakages and repairs accounts for irregularities in life-test curves such as are not seen in the curves of carbon filament lamps. This peculiarity of the metal-filament lamps raises a question in regard to proper criterion for reckoning the life of such lamps when testing them. The question is, should the life of a metal-filament lamp be reckoned up to the time when its filament first breaks or should the time of final failure be taken? In other words, should the first natural failure be considered as terminating the useful life of the lamps, or should the useful life include all the period up to the point where it is no longer possible by manipulating the lamp to cause it to repair itself?

Life History.

Some of the earliest tests of tantalum lamps made in this country showed a much poorer behavior than was claimed for the lamp by its makers. In these tests the lamps were burned on alternating-current circuits. Since there was no reason to suspect that the lamps were suffering on account of incorrect voltage or rough handling, the conclusion was almost inevitable that the nature of the current might be influencing their life. On trial it was found that tests made on direct current instead of alternating gave results which were in general agreement with those which had been published abroad. Since that time the effect of alternating current in shortening the life of a tantalum lamp has become well recognized. Since no quantitative data have been published showing the amount of this effect, the following table in which comparative values of the life of tantalum lamps on direct current and on alternating current of 25, 60, and 130 cycles per second will be of interest. The results of the 130-cycle test have kindly been placed at my disposal by the authorities of the Edison Lamp Works.

A microscopic examination of the tantalum filaments, new and burned on direct current and alternating current of different frequencies, is extremely interesting. A free-hand drawing of such filaments as seen under the microscope is given in Fig. 7.

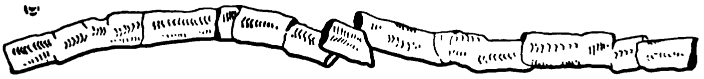
TABLE IV.

MORTALITY TABLE—TANTALUM LAMPS.

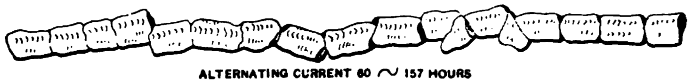
	130 Cycles.			60 Cycles	25 Cycles	Direct Current
	1.87 watts per candle	2.49 watts per candle	3.1 watts per candle	Rated volts	Rated volts	Rated volts
Number of lamps	10	10	10	15	16	20
First burn-out..........	34 hr.	92 hr.	110 hr	23 hr	177 hr.	180 hr.
50% burned out........	114 "	167 "	238 "	118 "	271 "	641 "
100% burned out.......	290 "	335 "	447 "	476 "	641 "	
Total hours of test......	290 "	335 "	447 "	397 "	641 "	775 "
Average life of group....	122 "	203 "	248 "	151 " (est.)	324 "	606 " (est.)

It will be seen in this figure that the unused filament is smooth and polished with only slight pittings on the surface. The filament which has been burned on direct current is much less regular; its surface shows deeper pittings and, in places, it is cut and notched as if with a knife blade. Some parts of the filament are much more irregular than others. The filament on 25 cycles shows still stronger markings of the same character as shown on the direct current, but shows also, in places, a jointed structure looking like the jointed structure observable sometimes in basaltic rocks. This latter effect is even more marked in the case of the filament which has been run on 60 cycles. Here, parts of the filament look as if they were made up of blocks which had been irregularly piled one on the other. The length of these jointed sections in the filament is about equal to the diameter of the filament itself. It looks, in some places, as if one of these sections had been almost expelled from the row. The appearance, too, is very much as if where these joints occur, the filament had actually separated and had welded itself together instantly. The filament which had been operated on 130 cycles had the same appearance, perhaps somewhat exaggerated. In short, the increased wear and tear of the filament, due to the use of the alternating current, is very apparent. The reason for it, however, is obscure. The conclusion is inevitable that this lamp at the present time is essentially a direct-current lamp.

No such effect is observable with the tungsten lamps. Tests of the Electrical Testing Laboratories show quite definitely that their life on direct current and alternating current is the same. This has also been proved by elaborate experiments to be true of carbon filaments.

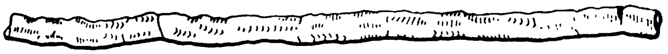


ALTERNATING CURRENT 130 ~ 300 HOURS

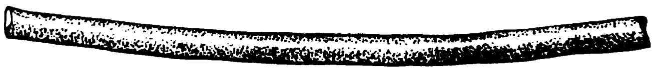


ALTERNATING CURRENT 60 ~ 157 HOURS

ALTERNATING CURRENT 25 ~ 467 HOURS



DIRECT CURRENT 492 HOURS



NEW LAMP

THE TANTALUM FILAMENT

Fig 7

The results of tests of 20 tantalum lamps of German manufacture on direct current are given in Table V. From these data the curves of Fig. 8 have been plotted.

Fig. 9 gives the average values of horizontal candle-power, watts, and watts per candle of the above lamps and it serves to show graphically the distribution of failures of the individual lamps.

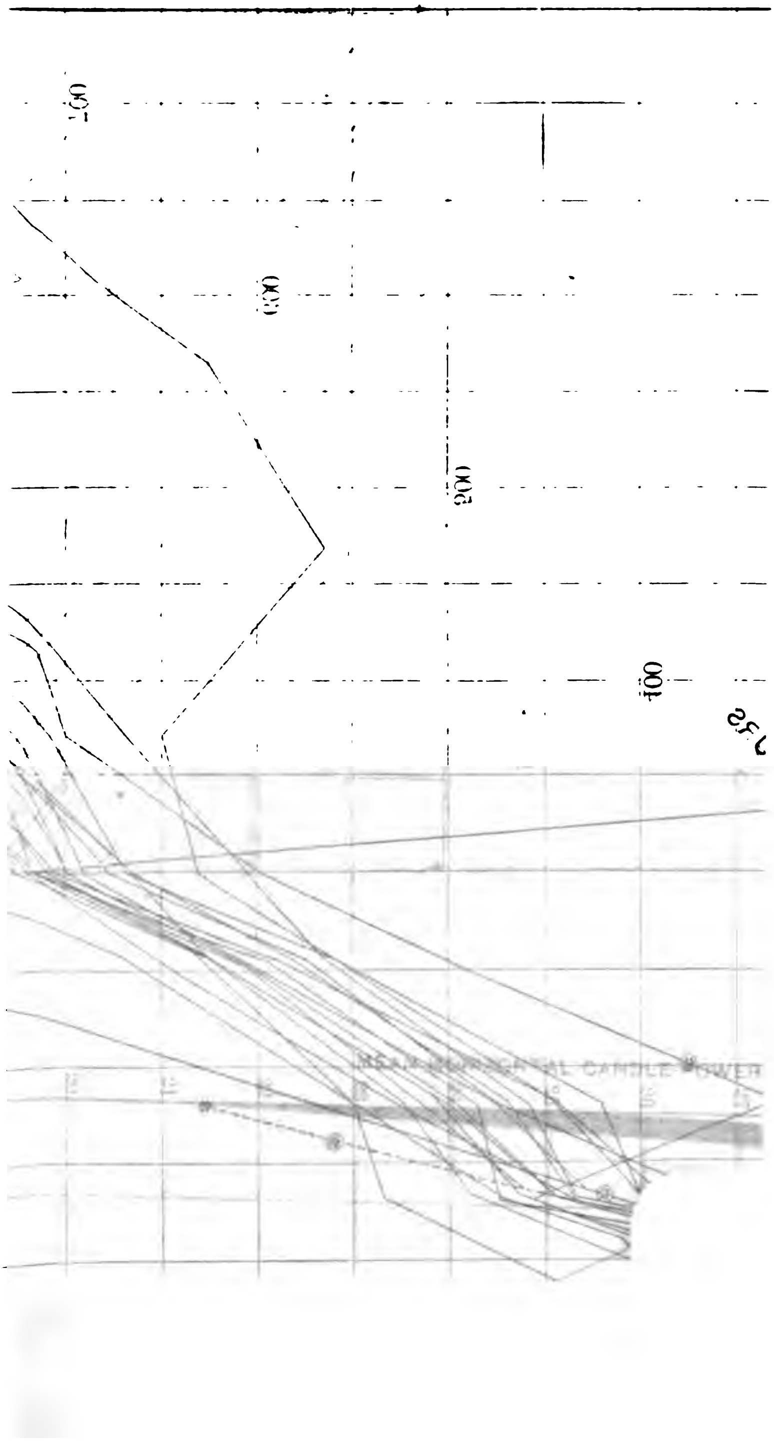

100
200
300
25
MEAN HORIZONTAL CANDLE POWER

TABLE V

DATA ON TEST OF GERMAN-MADE TANTALUM LAMPS ON DIRECT CURRENT

Lamp No.	Mean Hor. c-p.			Watts per c-p.			Hor	Sph Red. Factor.		Mean Sph. c-p.			Watts per m.s. c-p.			No. of Short Cir-cuits.	Life to B O.
	Init.	Mean	700 hr.	Init.	Mean	700 hr.	c.-hr.	Init	636 hr.	Init	700 hr.	Decrease	Init	708 hr.	Increase		
51	23.0	23.7		2.04	1.99		12233	0.734		16.9			2.78			2	516
52	24.4	23.9		1.98	1.98		7349	0.744		18.2			2.66			2	307
53	21.1	21.8	17.8	2.17	2.13	2.50	15284*	0.764	0.856	16.1	14.8	8.1%	2.84	3.06	7.7%	1	738
54	23.5	22.6	18.7	1.95	1.94	2.42	16026*	0.715	0.878	16.8	17.1	—1.8%	2.73	2.73	0%	2	738
55	25.5	21.9		2.05	2.28		13706	0.738		18.8			2.78			1	626
56	24.5	24.1		1.94	1.97		10427	0.721		17.7			2.69			2	432
57	25.2	26.9		1.83	1.72		4844	0.715		18.0			2.56			2	180
58	24.0	21.3		1.93	2.11		13685	0.736		17.7			2.62			2	641
59	23.4	26.4		1.91	1.70		13765	0.760	0.886	17.8			2.52			1	642
60	24.6	26.4		1.87	1.73		10876	0.730		18.0			2.56			1	412
61	23.7	20.6	15.7	1.94	2.20	2.80	14416*	0.738	0.938	17.5	14.3	18.3%	2.63	3.10	17.9%	1	
62	24.5	21.9	16.3	1.96	2.12	2.77	15374*	0.726	0.888	17.8	15.4	13.5%	2.70	2.95	9.3%	1	706
63	23.3	20.9		2.19	2.41		13133	0.730		17.0			3.00			2	629
64	23.9	23.0		1.98	2.00		11303	0.726		17.3			2.73			1	492
65	24.1	21.7	17.0	1.94	2.13	2.62	15184*	0.688	0.864	16.6	15.4	7.2%	2.82	2.92	3.6%	2	
66	23.2	21.2	15.8	2.04	2.14	2.83	14816*	0.716	0.909	16.6	17.3	—4%	2.85	2.71	—4.9%	2	758
67	21.8	20.3		2.13	2.30		14226	0.742	0.924	16.2			2.87			2	700
68	24.1	22.7		2.00	2.06		12231	0.727		17.5			2.75			1	539
69	24.2	21.2	17.3	1.98	2.21	2.74	14830*	0.707	0.902	17.1	19.8	—13.5%	2.80	2.53	—9.6%	3	738
70	25.3	21.4	19.3	1.92	2.22	2.50	14990*	0.711	0.925	18.0	18.7	—3.7%	2.70	2.66	—1.5%	3	737
Average	23.9	22.8	17.20	1.99	2.07	2.65	12935	0.728	0.897	17.4	16.6	3.0%	2.78	2.60	2.8%		

* Candle-hours to 700 hours.

Representative lamps, the performance of which may be considered to be characteristic of the 20 tantalum lamps, have been selected from among the above. Data on these lamps are given in Table VI and are plotted in Fig. 10.

From the foregoing data it will be seen that the life-history of tantalum lamps is characterized by a large initial increase in candle-power and a corresponding decrease in watts per candle,

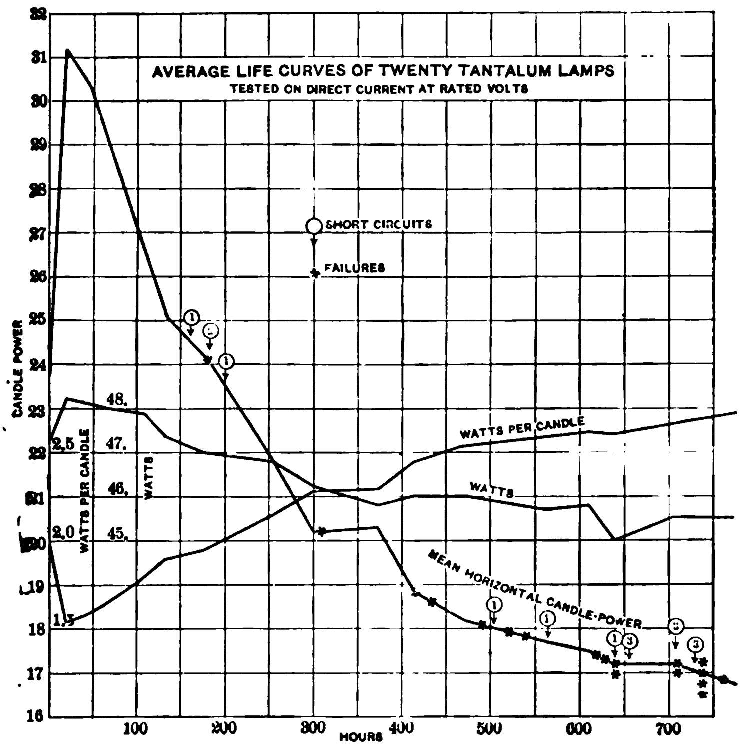


Fig. 9.

the extreme values being reached at the end of about 25 hours. From this point on, the candle-power decreases at a moderately rapid rate and the watts per candle increase. The rate of decline of the mean horizontal candle-power is more rapid than that of the mean spherical candle-power, for the reasons given above. The result of the relatively slow decrease of mean spherical candle-power with a large initial increase, is that in some cases the final mean spherical candle-power of a lamp is actually greater than its initial mean spherical candle-power. For purposes of ready comparison, life curves of representative tantalum and of a carbon lamp burned at 3.1 watts per candle are shown in Fig. 11. The candle-power of both is on a mean spherical basis. The exaggerated initial rise of the candle-power of the tantalum lamp is very apparent. Curves for watts per spherical candle-power give an opportunity for a comparison of the relative electrical economy of the two kinds of lamp.

Results of tests of tungsten lamps made in various laboratories are given below. The data on some of the makes of tungsten lamps are extremely meager, a circumstance which in some cases is believed to correspond to a backward state of their commercial development. Fig. 12 gives the results of tests* of two Kuzel lamps of approximately 30 volts and 11.5 candle-power, made at the Technologisches Gewerbe-Museum in Vienna. These lamps consumed approximately 1.25 watts per candle initially. One of them reached the extraordinary life of 3,537 hours, with a decrease in candle-power of about 10 per cent. The filaments in both the lamps were burnt through and repaired once in the course of their life. The result of the repair was an increased candle-power, which is shown clearly on the curve.

TABLE VI.

REPRESENTATIVE TANTALUM LAMPS. DATA ON LAMPS NOS. 69 AND 53.

	Mean Horizontal		Mean Spherical	
	Lamp No 69	Lamp No 53	Lamp No. 69	Lamp No. 53
Initial candle-power	24.2%	21.1%	17.1%	16.1%
Peak candle-power	31.6%	29.9%	22.5%	22.9%
700-hr. candle-power	17.3%	17.8%	16.0%	15.4%
Average candle-power to 700 hours	21.2%	21.7%	17.1%	17.6%
Decrease c-p. during 700 hours — From Initial	28.5%	15.6%	6.4%	4.4%
Decrease c-p. during 700 hours — From Peak	45.3%	40.5%	28.9%	32.7%
Rate of decrease per 100 hours during 700 hours — From Initial	4.07%	2.23%	0.91%	0.63%
Rate of decrease per 100 hours during 700 hours — From Peak	6 47%	5.79%	4.13%	4.67%
Initial reduction factor			0.764	0.707
Reduction factor at 635 hours			0.836	0.902
Average watts	46.6	45.8	46.6	45.8
Initial watts per candle	1.98	2.17	2.80	2.84
Watts per candle (peak)	1.52	1.59	2 12	2.07
Watts per candle (700 hours)	2 61	2.50	2.82	2.90
Average watts per candle	2 20	2 11	2 70	2.60

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*Kremenezky "Elektrotechnik und Maschinenbau," 1906, No. 6.

The average result of tests of three Osmin lamps of 55 volts and 44 candle-power are shown in Fig. 13. These tests were made in the laboratory of an electrical company in Vienna. The lamps showed a life of 1,200 hours and a decrease in candle-power of 14 per cent. in that time. The results of a test of three

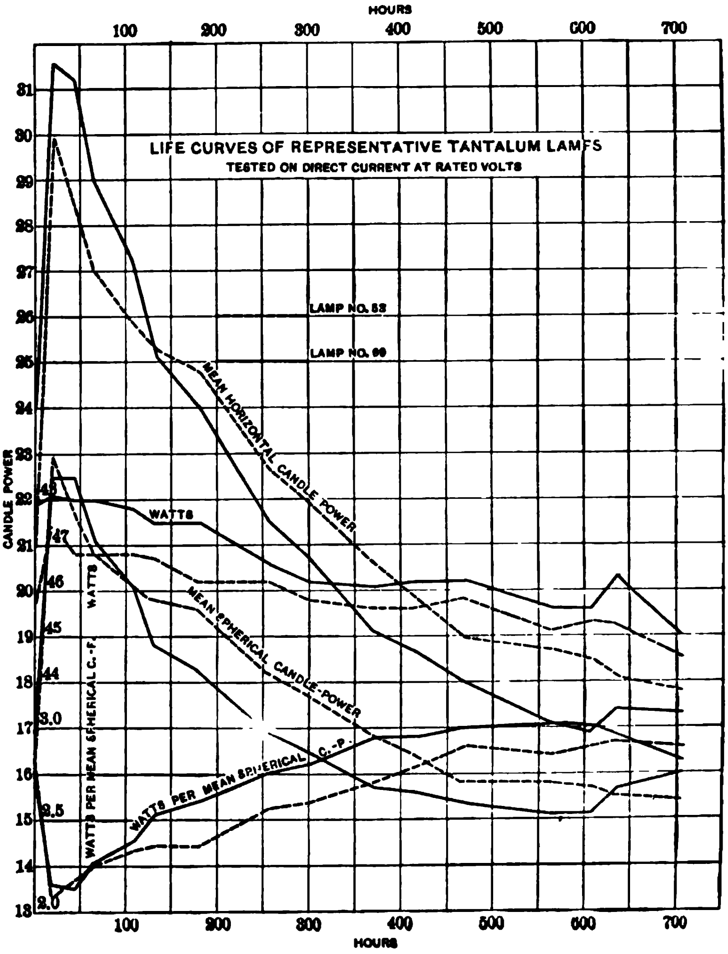

Fig. 10.

Osmin lamps of 55 volts made at the Municipal Electricity Works, Vienna. showed an initial candle-power of 27.3 and initial watts of candle-power of 1.25. After 2,239 hours of burning the candle-power was 23.4 and the watts per candle 1.45. Six 54-volt Osmin lamps tested at the Technologisches Gewerbe-

Museum consumed initially 1.17 watts per candle. After 1,776 hours the watts per candle were 1.24. The candle-power of these lamps is not given in the report. It should be noticed that all the above lamps are low-voltage lamps, from which a better result is to be expected than from 110-volt lamps.

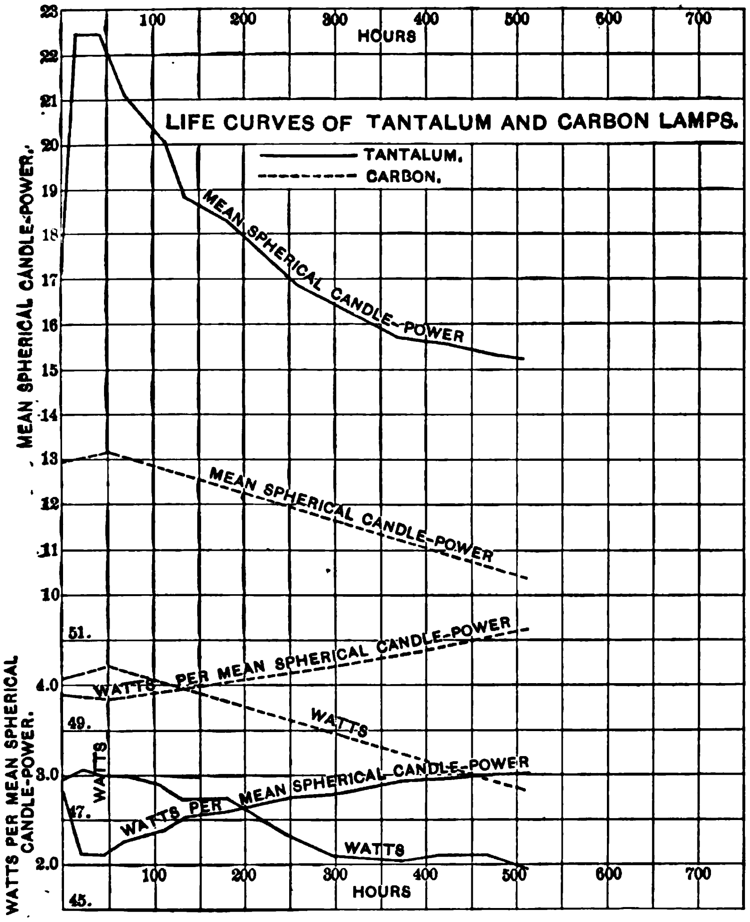

FIG. 11.

The results of tests made at the Reichsanstalt of 16 Osram lamps of from 117 to 111 volts and 25 to 30 candles are shown in the curves of Fig. 14. This test extended for 1000 hr. In the course of that time 5 out of a total of 16 lamps had failed, while 11 lamps were still burning. The characteristics of the lamps seem to be a moderate initial rise in candle-power and a very slow subsequent rate of decline.

Fig. 15 shows average values of candle-power, watts, and watts per candle of eight 117-volt lamps from among those given in the above tests.

In Fig. 16 are shown the individual curves of six Osram lamps of 32, 35, and 45 c-p, tested at the Electrical Testing Laboratories. The results of these tests differ from the results of the Reichsanstalt test in that they show practically no initial rise in candle-power. The decrease in candle-power of the lamps throughout life, however, is very slow. The watts per candle are also almost constant. The life of the lamps was on the average considerably shorter than the life of those tested at the Reichsanstalt.

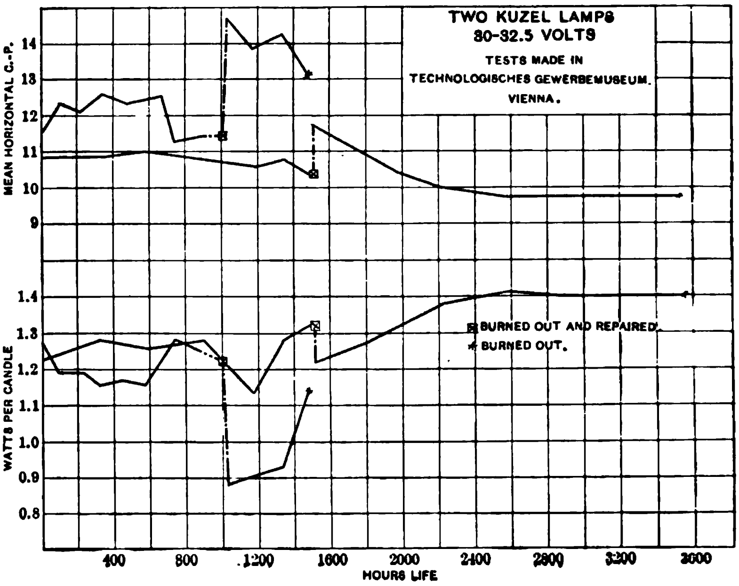

FIG. 12.

Candle-power curves of eleven tungsten lamps of quite another foreign make as tested at the Electrical Testing Laboratories are shown in Fig. 17. These lamps exhibit a very large initial increase in candle-power, followed by a practically constant condition. The average life is also much shorter than in the case of the Osram lamp.

The curves of Fig. 18, furnished by courtesy of Mr John. W. Howell, are of particular interest since they show the performance of lamps made in this country. These lamps were tested at an average initial consumption of 0.99 watts per candle. Their average life was 363 hours even at this high initial efficiency, and the average decrease in candle-power was 17.7 per cent. These curves demonstrate that incandescent lamps can be produced which will operate successfully at one watt per candle

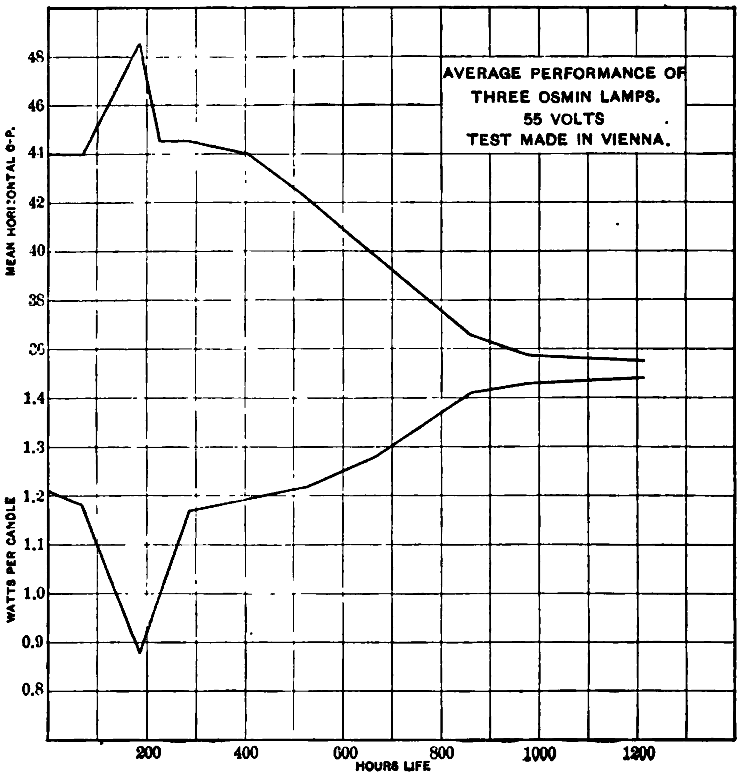

Fig. 13.

and will give a satisfactory life. The candle-power of these lamps averaged about 40.

The successive changes in the operating regime of incandescent lamps represented by the decrease in watts per candle from 3.1 to 2.0 and 1.25 as in the tantalum and tungsten lamps, mark a prodigious advance in the art of electric lighting. How great this advance really is is illustrated more strikingly if we consider the relative life of these lamps burned at the same initial watts per candle as the tungsten lamp normally consumes. The results of a life test conducted on this basis are given in Fig. 19. The effective life to 80 per cent. of initial candle-power of the carbon lamp was 2 hr. and 38 minutes; of the tantalum lamp,

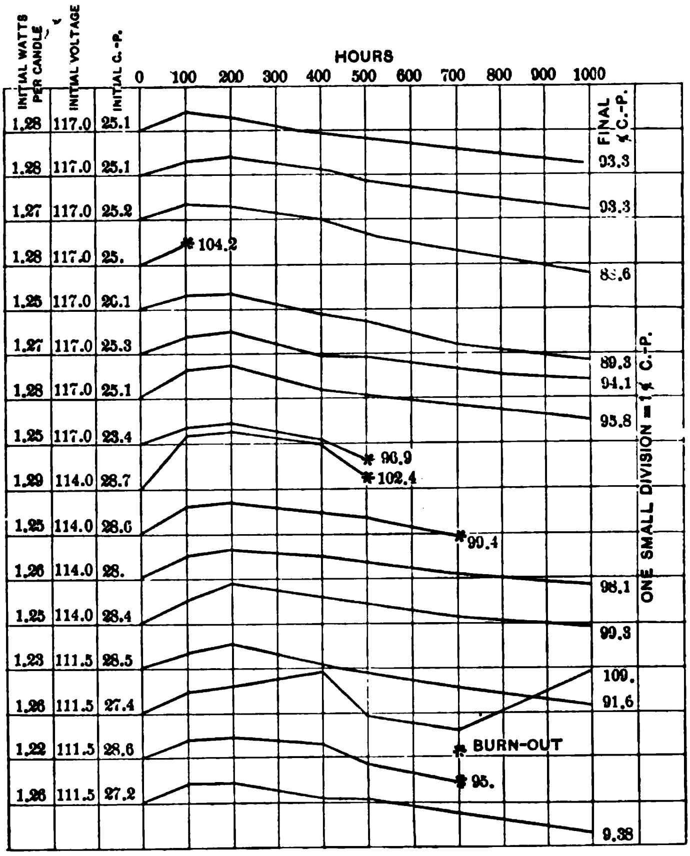

FIG. 14.—Candle-power Curves of Life-Test of Tungsten Lamps, Made by Physikalish-Technische Reichsanstalt on Alternating Current and Reduced to British Units.

52 hr, while the tungsten lamp was burning with practically unchanged candle-power after the test had continued more than 700 hr.

COLOR OF LIGHT AND EFFICIENCY.

The color of the light from the tantalum lamp is whiter than that of the carbon lamp, and the color of the tungsten lamp is still whiter than that of the tantalum lamp. The light of the tungsten lamp resembles quite closely that of the acetylene flame. The increased whiteness of the light, which is produced evidently largely as a temperature effect and which does not involve a preponderance of certain colors, such as green or violet, constitutes a point of real superiority in the tungsten lamp. Time has been lacking to make a regular spectro-photometric study of these lamps. A simple experiment, however, has been made

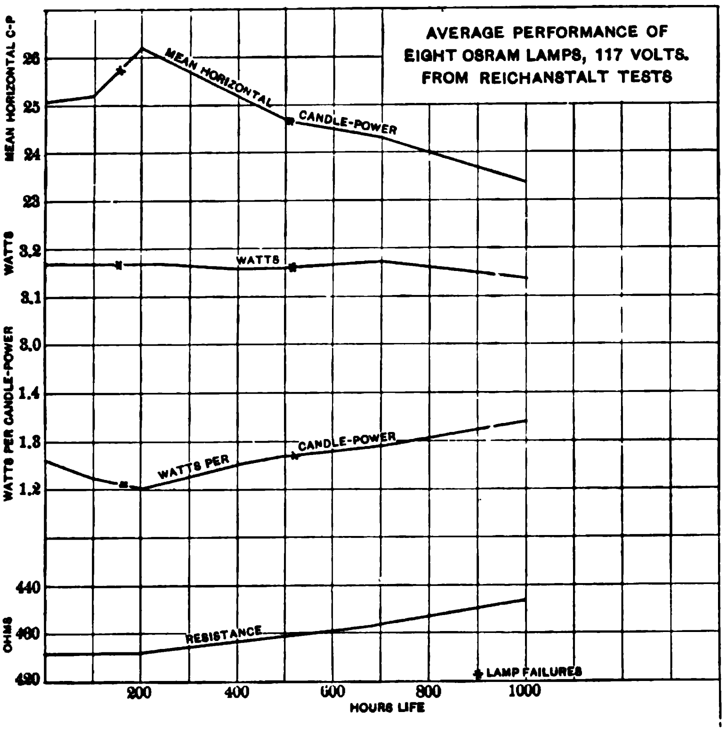

FIG. 15.

which gives some idea of the increased radiation of the shorter wave lengths, both of tungsten and tantalum lamps, as compared with the carbon lamp at 3.1 watts per candle.

The metal-filament lamps where photometered against the 3.1-carbon lamp directly and then with a red, green, and blue glass interposed between the eye and the eye-piece of the photometer. The intensities so measured, expressed in percentages of the intensities measured without colored glasses, are given in the following table:

TABLE VII.

	Tantalum Lamp.	*Tungsten Lamp.*
Total light	100%	100%
Red light	90.5	83.0
Green light	100.3	101.8
Blue light	109.2	126.5

The increased whiteness of these lamps may theoretically be due either to higher temperature of the filament or to selective radiation by the filament. Recent work of Waidner and Burgess indicates that while the increase in the efficiency of tantalum and tungsten lamps, as compared with the carbon lamp, is to some extent due to the selective character of their radiating power, yet the chief cause of the increase is the higher temperature at which it is practicable to operate them. The higher temperature causes the maximum of the spectral energy curve to

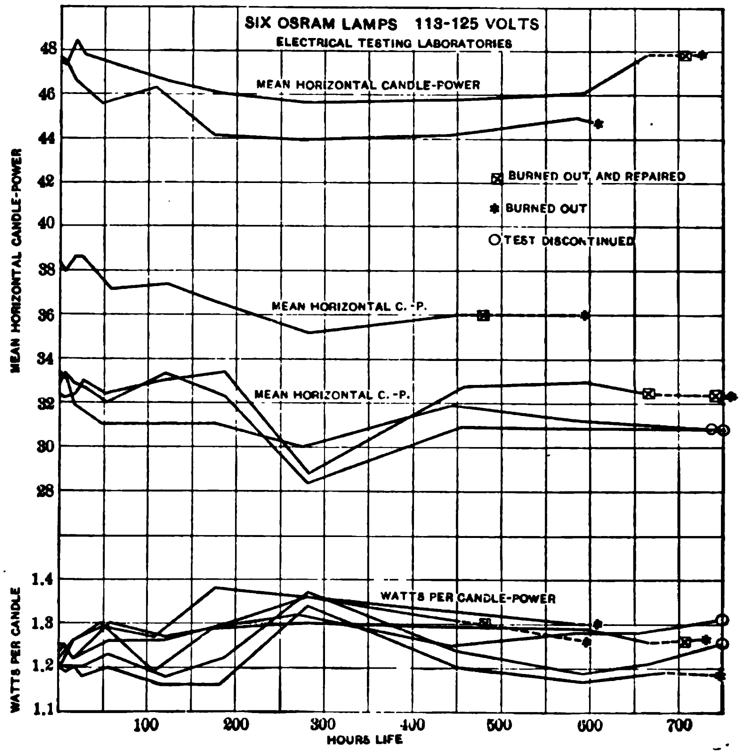

FIG. 16.

be shifted toward the shorter wave-lengths, and consequently a higher percentage of the total radiation is emitted in wave-lengths which are capable of exciting vision.

Flickering on Alternating Current.

It has been established as a result of practice that in general it is not possible to operate incandescent lamps on 25-cycle current with satisfactory results. This statement is made with a knowledge of the fact that in certain cities a large amount of lighting is actually being done on 25-cycle circuits. Yet under some circumstances 25-cycle current produces such marked flickering of incandescent lamps that its use is absolutely impossible. It is an interesting question whether the tungsten lamp presents any advantages over the carbon lamp for use on low-frequency circuits. Its positive temperature coefficient and the relatively

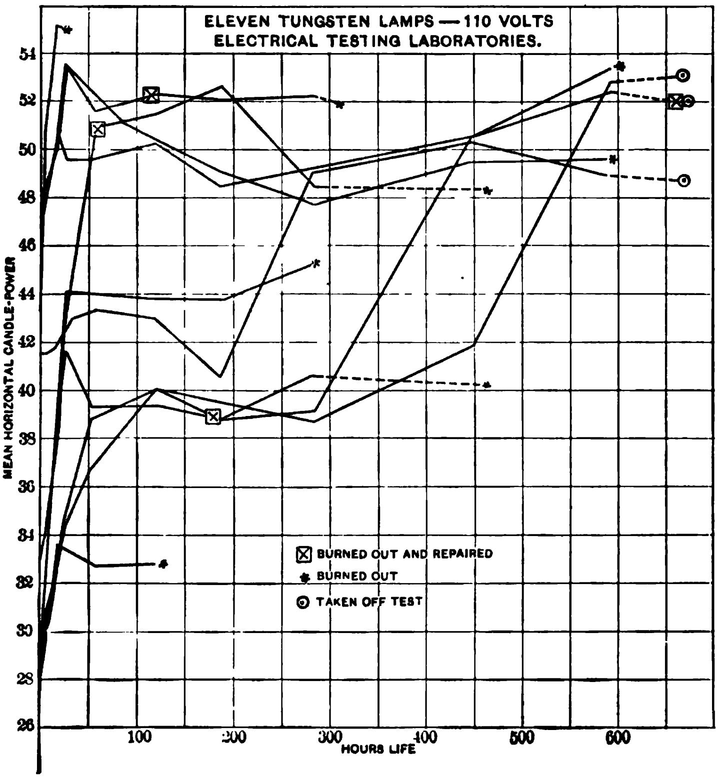

Fig. 17.

low radiating power of its surface would tend to reduce the flickering, while the extreme fineness of the filaments which results in a smaller thermal capacity and the high thermal conductivity which, as a metal it probably possesses, would tend to increase the flickering. A few preliminary tests have been made

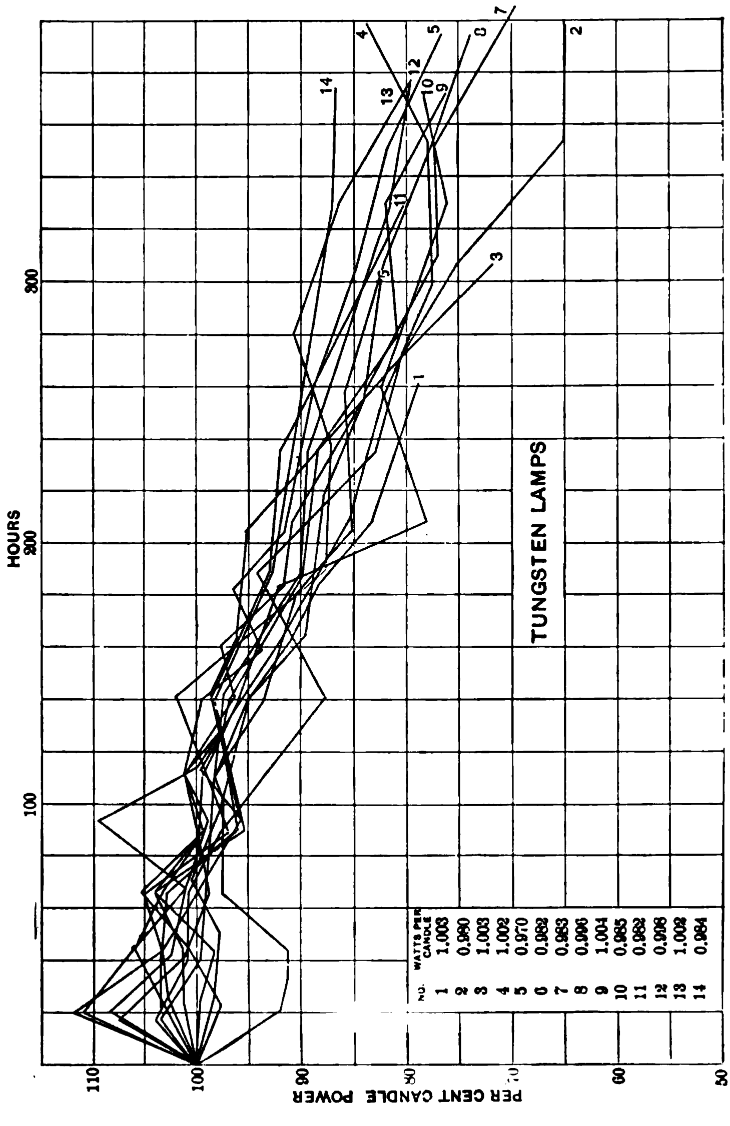

FIG. 18.—American made tungsten lamps.

in an attempt to gain some information on this question. It was very quickly discovered, however. that the question is so very complicated that a considerable research will be required to ascertain definitely the facts of the case. Eleven tungsten lamps were attached to the ceiling of a small room, producing a brilliant illumination in the room. Three observers attempted to determine the presence or absence of flickering. With the lamps at their normal voltage of 115 and with a frequency of 25.5 cycles per second, L. found the flickering marked; M. found the flickering marked; S. could see a flickering intermittently, as when his head was moved suddenly. With the same lamps, but with the voltage reduced to 100, the flickering was imperceptible to all the observers

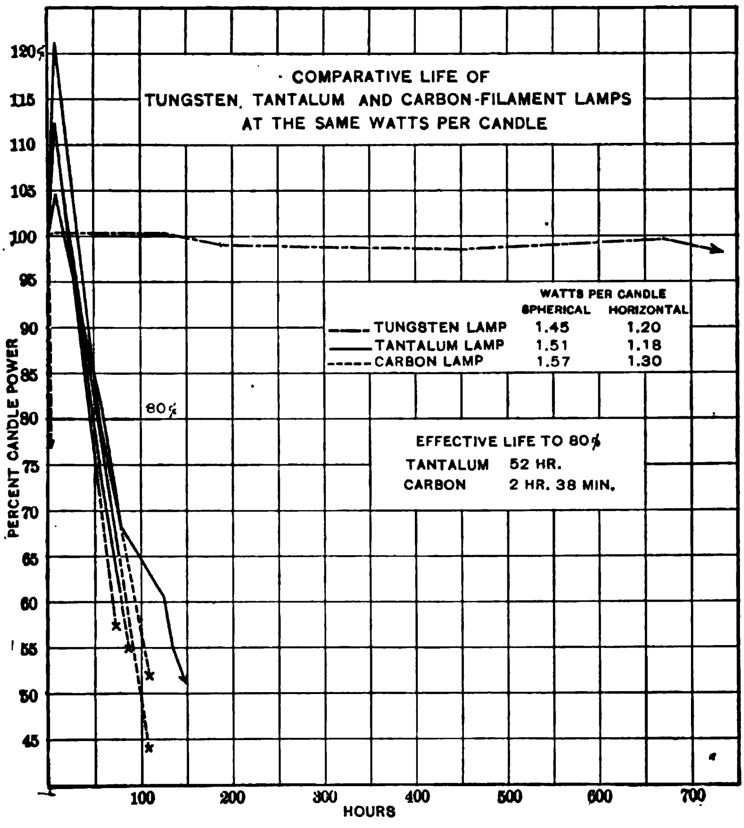

FIG. 19.

As the voltage was raised successively to 105 and 110 volts the flickering became perceptible. When five of the lamps were removed, leaving only six lamps in position, it was the consensus of opinion of the three observers that the flickering was less marked than when all the lamps were in. In other words, the intensity of the sensation of flickering seems to be a function of the illumination. The flickering was imperceptible when looking directly at the lamps, but could be observed only through light which is not focused directly on the fovea of the eye. To institute a comparison between the flickering of the tungsten lamps and of carbon-filament lamps, two procedures may be taken.

1. To take a sufficient number of carbon-filament lamps of candle-power comparable to the candle-power of the tungsten lamps, lamp for lamp.

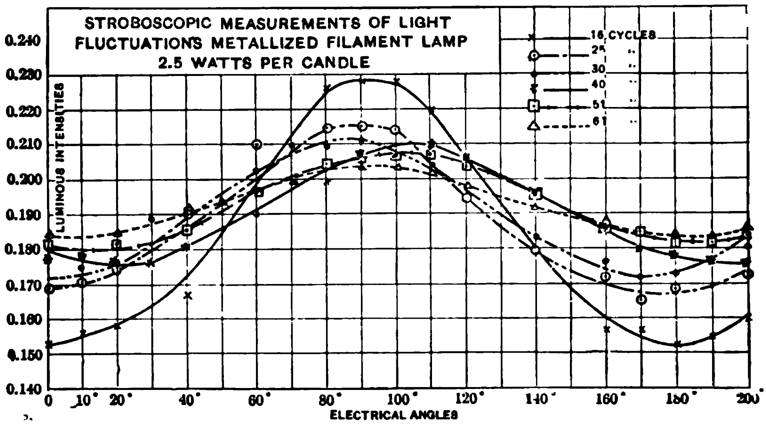

Fig. 20.

2. To take a sufficient number of carbon-filament lamps having a filament of approximately the same diameter as the diameter of the tungsten filament.

The numbers of the carbon-filament lamps must be so chosen as to give substantially the same amount of light as the tungsten lamps. The first of the two above alternatives was chosen for a comparative test. That is to say, twelve 32-c-p. carbon lamps were substituted for the 11 tungsten lamps. These were operated at 3.1 watts per candle. At the same frequency as was used for the tungsten lamps, no flickering could be observed. This is not a surprising result, since the diameter of carbon filaments is much greater than the diameter of the tungsten filaments, and consequently their thermal sluggishness is a much more important factor.

In view of the very considerable advantages which would be gained if it could be shown that it is feasible to operate incandescent lamps on alternating-current circuits of frequency low enough to permit of the easy operation of synchronous converters, that is to say, a frequency of 25 cycles or slightly greater, the question of the variation of the light of incandescent lamps during a half cycle of the alternating current has also been subjected to an experimental investigation by the use of a stroboscope. To the axis of a small synchronous motor was attached

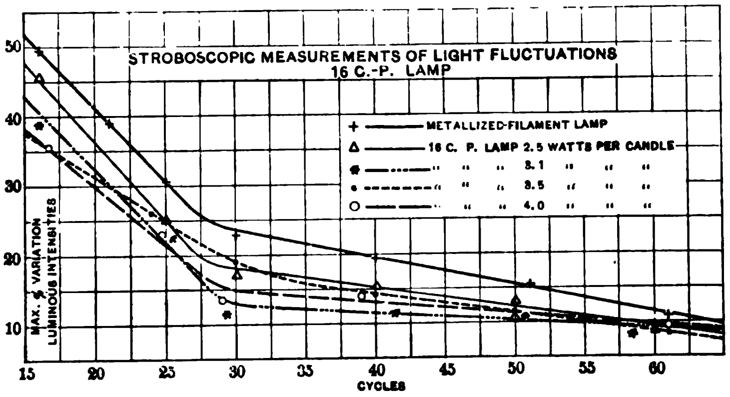

FIG. 21.

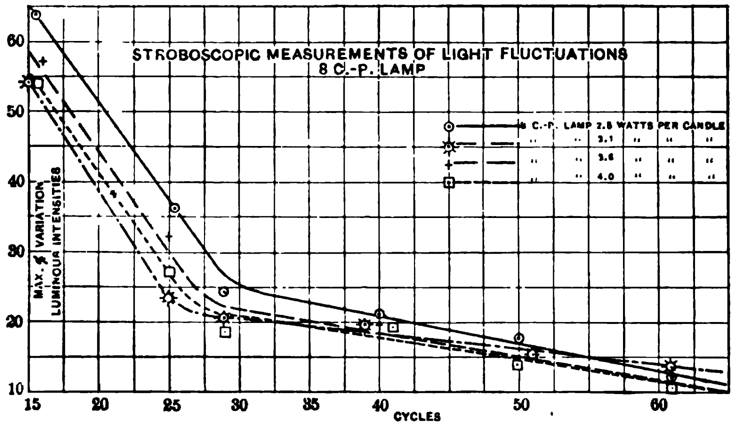

FIG. 22.

a disc with narrow radial slots cut in it, one for each pole of the motor. The lamp was placed behind this disc, while close to it and in front of the disc a suitable photometer was arranged. The motor was driven from one of two alternators, having their shafts coupled together, and the lamp was supplied from the other alternator. The phase of the current passing through the lamp with respect to the current in the motor could be shifted through known angles by shifting the armature ring of one of the coupled generators. This generator arrangement, which was planned originally chiefly for meter tests, proved itself to be extraordinarily convenient for such stroboscopic measurements as are here described. With the use of this arrangement, curves have been plotted showing the variation in the intensity of the incandescent lamps as the current through the lamp rises from zero to its maximum value and decreases to zero once more. A set of curves of this kind relating to the metallized-filament lamp operated at 2.5 watts per candle, are reproduced in Fig. 19 and serve to illustrate the nature of the data obtained. Similar curves were obtained for ordinary 8- and 16- c-p. lamps, operated at a series of different values of the watts per candle.

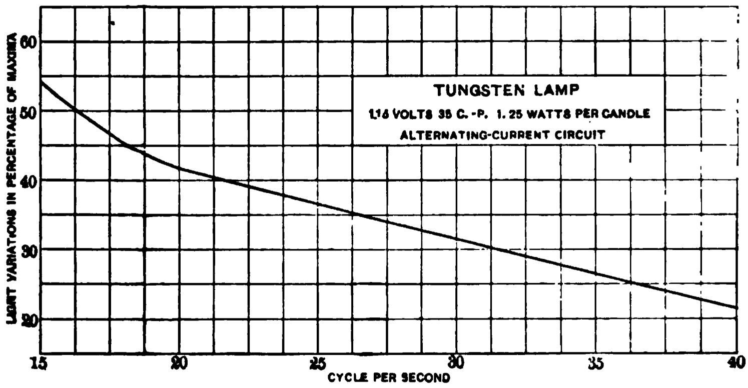

FIG. 23.

To discuss these results, the percentage variation of the light of the lamp per cycle was taken under all the different conditions. These percentage variations were plotted in curves shown in Figs. 20 and 21, using frequencies as abscissas. The curves so obtained, while exhibiting certain irregularities due to experimental difficulties, are fairly concordant and exhibit to a common character. The percentage variation seems from these curves to be expressible by two linear relations, with a point of sharp curvature occurring between 25 and 30 cycles per second. That is, as the frequency is increased from 15 to 25 cycles the diminution in flicker is very rapid. Above 30 cycles the diminution in flicker is very slow. Since it has been found possible in some places to operate incandescent lamps on 25 cycles, it would seem probable that a comparatively small increase in the frequency, which would carry the lamps beyond this apparently critical point in the curve, might make feasible the general operation of incandescent lamps from alternating-current power circuits.

Similar tests to the above have been carried out on a 40-watt, 35-c-p, 115-volt Osram lamp. The results of this test as shown in Fig. 22 indicate that the stroboscopic variations of a tungsten lamp of this size are not much different from those of an ordinary lamp rated as an 8-c-p. lamp when forced to 2.5 watts per candle. The stroboscopic measurements, however, may be subject to certain ones of the difficulties which affect the detection of flicker by the eye. In other words, the degree of intensity of the light upon the photometer disc may have an influence on the results obtained. However, if the results of this preliminary test, which has been made in a very limited time for the purposes of this paper, can be confirmed by later and more careful experiments, the tungsten lamp will be found to be less adapted to use on alternating circuits of low frequency than the standard lamp of to-day.

CONCLUSION.

From the data given above it seems certain that the electric lighting industry is face to face with a change of almost revolutionary character. The standard of incandescent lighting efficiency will be brought by the tungsten lamp to a point about three times as high as it is at present. The efficiencies of all other incandescent lamps and of enclosed arc lamps are exceeded by that of the tungsten lamp. In other words, with the possible exception of some forms of vacuum-tube lighting and of the magnetite and flaming arc lamps, the tungsten lamp is the most efficient electric illuminant. Combined with its virtue of high efficiency it has the other advantages of incandescent lamps in being perfectly simple in its character and construction and in being capable of subdivision into small units.

DISCUSSION ON " TRANSFORMATION OF ELECTRIC POWER INTO LIGHT," AND " NEW TYPES OF INCANDESCENT LAMPS," NEW YORK, NOVEMBER 23, 1906.

Herschel C. Parker: The problem of the transformation of electric power into light is of equal importance to the physicist and to the electrical engineer. When an electrical engineer experiments on the problem, he is experimenting in the domain of physics; when a physicist works on the problem, he is an electrical engineer, if his experiments are successful; if not, he is simply a physicist. There are only two or three points in Dr. Steinmetz's beautiful paper on which I am capable of saying anything that will interest you. The first is the fact that it is not the melting point of refractory substances that gives a high efficiency, but it is the point of disintegration or vaporization, shown by the tungsten filament and tantalum filaments which have a much lower melting point than carbon, but are much more difficult of vaporization, and hence show a great increase in efficiency. Mr. Walter G. Clark and I have been experimenting for a number of years on the subject of incandescent lighting, and we hope in the near future to present before the Institute some of these results which we think are of interest. A certain filament with which we have been experimenting, one substance of which is supposed to have a melting point of about 1400° cent., has shown an efficiency in experimental lamps of about one watt per candle, with an average life of 700 to 1200 hours. The vapor-tension of this substance is remarkably low; that is, it is almost impossible to vaporize the substance. This bears out in a remarkable manner the statement of Dr. Steinmetz. Another point about this filament is that if at the low temperature of 1800° or 1900° cent., it will give an efficiency of one watt per candle, we certainly must believe that some substances have a considerable selective radiation in the solid form, notwithstanding what the experiments of Messrs. Waidner and Burgess have shown regarding the tungsten and tantalum filaments.

Dr. Steinmetz's remarks about vapors, that we have the most intense selective radiation without respect to temperature, is shown in a wonderful manner by the experiments in connection with the electrodeless discharge. Mr. C. C. Trowbridge has carried on some very elaborate experiments in this field at Columbia University, and has shown that when the receiver is surrounded by liquid air a very considerable luminescence can be obtained and be continued for a number of minutes after the electrical disturbance has been discontinued. His calculations show that if the number of molecules in the rarefied gases could be increased, and the same effect obtained, the efficiency would be enormous, approximating 100 per cent.; that is, we can have luminescence in the gas that is absolutely independent of temperature.

Concerning arc lamps and their efficiency. I am glad to get some little idea of what the efficiency of these flaming arcs really is. If the efficiency is one-quarter watt per candle and the efficiency of the incandescent lamp is one watt per candle, since we have a superior means of distribution with the latter and the illumination is in terms of the normal daylight spectrum, the absolute illuminating value would not be far behind the arc lamp at one-quarter watt per candle; but experiments we have been carrying on indicate that it may be possible to reach an efficiency approximating one-half watt per candle, and that in terms of the normal daylight spectrum. There would then be no question that with such a high illuminating value the incandescent lamp would be fully equal, if not superior, to any form of arc lamp known at the present time.

John W. Howell: Practically all of the efficient illuminants mentioned to-night originated abroad. We have the Welsbach mantle, which marked a great advance in the efficiency of gas lighting, the osmium lamp, the tantalum lamp, the Nernst lamp, the tungsten lamp, the flaming arc—all originating either in Germany or in Austria.

Dr. Sharp presents a table in which it is shown that the carbon filament, from 1888 to 1904, sixteen years, improved 2.5 times in value in life at the same efficiency. He also shows a curve which indicates that the tungsten lamp is at least 300 times as long lived at the same efficiency as the carbon lamp, even after its sixteen years of improvement. It is hard to realize what that means. It means, as both the papers have stated, a revolution in the art of incandescent lighting, and of all lighting. This tungsten filament, from the nature of the material, can be most easily made in rather large candle-powers. Dr. Sharp puts 25 c-p. as the lower limit, but the really practicable lower limit is higher than that. I think that 40 c-p. would be about the lower limit at 110 volts; for lower candle-powers, lower voltage lamps will have to be employed either in series or in other ways. But while that is the limit, it fits exactly in the place where the carbon filament is weak. Above 40 c-p. the carbon filament is weak and the tungsten filament is strong. The tungsten filament from 40 to 200 c-p. is at its best. At these candle-powers, the incandescent lamp, with its distribution and stability, is better than twice that candle-power in an arc lamp; and I look to the tungsten lamp as a probable competitor of arc lamps, and for other forms of light, the values of which lie between 50 and 200 c-p.

These curves shown in Fig. 14 were made at the Reichsanstalt.

The lamps were sent there on the 25th day of April, 1906, but before that time another set of these same lamps had been burning at the Reichsanstalt. I saw the records of these other lamps, and got a copy of them. They were set up at 1.3 watts per hefner, and burned 700 hours, and at the end of the time each one of the lamps was higher in candle-power and of better efficiency than when it started. That is probably the first recorded test on 110-volt tungsten lamps. The high temperature of the tungsten lamp is of course a large element in its efficiency. The selective radiation is described by Messrs. Waidner and Burgess, and it is shown that the quality of the radiating surface has also a great deal to do with it. The carbon lamp is a much better radiator of heat than a metallic filament. The more polished the metallic filament the worse radiator it is, and the more slowly it radiates its energy at a given temperature the more slowly energy has to be supplied to it to maintain the temperature. As Messrs. Waidner and Burgess state, a polished platinum wire is the most efficient metallic light-giving body. Some of the tungsten filaments approach very closely in appearance to polished platinum wire, and I think those forms will be more efficient than the others which do not approach that condition.

Percy H. Thomas: Dr. Steinmetz gathers together and summarizes the latest information as to the general nature and the best performance of the various kinds of devices for getting light from electric power. Dr. Sharp has certainly brought us up to date on the subject of incandescent lamps.

As I understand Dr. Steinmetz, he attributes the superior efficiency of gases as a source of light to the fact that their radiations are, relatively speaking, largely in the visible spectrum. This is undoubtedly true. A more satisfactory idea of the distinction between solids and gases as to their light-giving characteristics, can be gotten by considering the corpuscle theory of electricity in its relation to the emission of electric radiations by hot bodies. By many scientists light is assumed to consist of electromagnetic waves produced by vibrations within the atom, or by vibrations of the body of the atom itself. In this view the atom may be said to send out light waves when agitated, in the same way that a bell sends out sounds when struck with a hammer. As these sounds are of one pitch, or of a few related tones, so are the colors of light given by an atom of gas of one color or a comparatively few related colors. In an incandescent solid, light rays are still given out by the atoms themselves, but these atoms are so crowded by other atoms that they cannot vibrate in their natural period and all colors of light result. Furthermore, a great deal of energy is given off in heat radiations which are due to the translatory motion of the atoms and molecules backward and forward. Evidently, the natural time-period of vibrating molecules will be much lower than that of the vibrations within the atom, the former corresponding to the longer heat waves. As Dr. Steinmetz has said, these heat waves are a necessary waste of energy in the production of light.

Returning now to the emission of light by molecules of a gas; as, for example, in a Cooper Hewitt lamp. Here we have a number of presumably isolated vibrating atoms, and a series of projected corpuscles representing the current and passing from the negative to the positive electrode at very high velocities. These corpuscles must frequently strike atoms, and in so doing cause both the deformation or bell-like action and also a translatory motion. But, since they are of extremely small mass and high velocity, they will produce a large percentage of vibration and a small percentage of translation corresponding to an efficient production of light. This hypothesis tends to confirm an observed fact; namely, that those gases or vapors having relatively large atomic weight are more efficient sources of light when excited by electric current. For in such cases the relative amount of translation in relation to the internal vibration for the relatively heavy atom will be less than for the relatively light atom. Dr. Steinmetz has linked the efficiency of light sources with the boiling point of the materials giving a light. In some ways it appears to me more likely that differences in atomic weight rather than differences in boiling points determine the efficiencies.

Another point of a very much more practical nature is worth considering. We have covered pretty well the theoretical considerations governing the absolute, or what you might call the physical efficiency of the different methods of producing light. This physical efficiency is very important, but must be considered in connection with other practical considerations before it is applied in actual cases; that is, there are other things besides the physical efficiency which determine the usefulness of a lamp. For example, there must be inherently in such lamps as arc lamps, where the air and other gases are in contact with the hot bodies, a convection loss of heat, allowed for only incidentally by Dr. Steinmetz, and which may be of material importance. This fact will tend to decrease the advantage of the arc lamp over the incandescent lamp.

The size of units is of very great importance. This point has already been raised. A source of light which has for its smallest practical unit two or three thousand candle-power, like some of the flaming arcs, cannot get the advantage of its high efficiency because so much light at one point cannot be used economically. The contrast between the locations of a superabundance of light and locations more remote from a lamp with little light, interferes materially with the effectiveness of even that value of illumination which does exist in the darker portions.

High intrinsic brilliancy in a light source is harmful, in that it causes a contraction of the pupil of the eye even when the light is not directly in line of vision, so that comparatively ineffective use is made of the available illumination. This is a matter of the very greatest importance which has not until recently been fully realized. The arc light, especially the open-air arc light, the flaming arcs, and the bright incandescents suffer from this cause. Evidently the tube lights, such as the Moore tube and the Cooper Hewitt lamp have a great advantage over the other types in this regard, and furthermore cause no sharp shadows.

Greatly to the advantage of the Cooper Hewitt lamp, as Dr. Steinmetz points out, the colors of light most easily and naturally utilized by the eye are those in the middle portion of the visible spectrum, the yellows and greens. The Cooper Hewitt lamp is the only electric light having a majority of its light of these colors.

Walter G. Clark: In paying my respects to Dr. Steinmetz's most excellent paper, I wish to state that in connection with the experiments which are being conducted by Professor Parker and myself, I have had an opportunity to note the behavior of carbon filaments, and it has been my impression for some time, that the vaporization of carbon from the carbon filament is far in excess of that warranted by the temperature of the filament. Carbon maintained at a high temperature by an external source of heat, but within a quartz receptacle, did not show the vaporization that it did at a much lower temperature when the heat was produced by passing a current through it.

A number of experiments of this character together with the study of the filaments themselves have led me to believe that the ordinary filament is not of even temperature, but is made up of very narrow zones or spots of high incandescence and possibly, in an unflashed filament, of actual arcing in some places. The temperature which we observe most likely is the mean of a series of high-temperature and low-temperature spots, these would of necessity be very narrow; but from the fact that the filament is originally made up from a material which must pass off as a gas during the process of carbonizing, it must leave the filament somewhat porous. As the surface is carbonized before the interior, the gases leaving the interior would break through any surface-seal formed by the carbonizing of the surface and reduce the cross-section of the filament at that point; in an unflashed filament there would be a tendency to form a small arc across the gap in shunt with the continuous portion of the filament back of it. In flashing, these spots would be the first to be covered with the dense low-resistance carbon deposited out of the hydrocarbon, and as the temperature is excessively high at this point and the carbon deposited is of very low resistance, compared with the porous unflashed portion, the tendency is to over-deposit; for the carbon is not only deposited at the actual point of the greatest temperature, but for some distance on either side, so that while flashing improves the filament it does not entirely eliminate the high-and-low temperature conditions. But the temperature of a carbon filament probably represents the mean of a great number of extremes of high-temperature and low-temperature zones, and the carbon is vaporized from the high temperature points at an increasing rate until the filament parts.

With the graphitized or metalized filament, the conductivity is more nearly uniform on account of the greater per cent. of dense carbon, so it is possible to operate the filament at a higher temperature. I am of the opinion that the hot-point conditions also hold where metallic filaments are made up of colloidal tungsten particles, for the current passing through the filament at the time of the cintering[1] together will follow the path of lowest resistance where the arcing between the particles welds them together; and particles not directly in the path of the current may not become an active part of the filament. The arcing between the particles would continue until the points of contact fused together, when the temperature would immediately drop below the fusing point, but the points of contact would still represent the points of greatest temperature. On account of the fineness of the particles in the Kuzel filament, these zones of maximum and minimum temperature would be very close together. This condition may account for the higher resistance and high temperature coefficient of this type of filament.

It has been noted that some metallic filaments which are white in color at low temperature still radiate as black bodies. I have noted in some experiments that some white metals turn black before they begin to radiate light. Steel of a light gray or silvery color and confined in a vacuum, passed through several changes of color to black before it began to radiate light at the red end of the spectrum; this was also true of platinum, iridium, and copper, but did not appear to be true of aluminum. I was careful to remove the oxide from the surface of the aluminum and place it in a receiver filled with hydrogen, which I pumped out to create the vacuum, still a film of oxide may have formed which concealed the color-change; but experiments with thorium oxide, oxide of aluminum, flocculent silicon dioxide, calcium oxide, and a number of other white oxides or white-oxide forming materials indicated that they luminesce or become incandescent direct from their own white color to the characteristic light or wave-lengths which they emit without passing through all of the longer wave lengths leading up to and through the red end of the spectrum. I have also noted that it is possible to make a non-luminous gas flame luminous by charging it with a silicon vapor which broke up and gave silicon dioxide upon coming in contact with the

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[1] Fusing particles together by passing current through.

air. I have found it difficult to prevent the oxidization of silicon when in contact with air at high temperatures. I do not understand the statement that the silicon arc is non-luminous, assuming that Dr. Steinmetz is referring to an open arc. The oxidization of carbon in the arc would, of course, produce a gas which would show little if any luminosity, but the oxidization of silicon produces dioxide and in my experience becomes luminous at a comparatively low temperature, and an open arc from silicon should form the dioxide and become luminous.

The desirability of obtaining a light which covers the entire range of visible wave-length is brought out very well in this paper, but instead of endeavoring to obtain this entire range in one material or in two similar materials, as in the magnetite-titanium arc, may we not secure an efficient result by combining materials which show high efficiency at each end of the visible spectrum? For instance, if we were able to combine the mercury vapor arc with a light from a material which showed its highest efficiency in the red end of the spectrum, the resultant light should be both satisfactory and economical. The carbon filament is, of course, not sufficiently efficient when maintained at a temperature where the red rays predominate, but a combination of the Geissler tube effect with the mercury vapor arc would be a step in this direction.

The matter of selective radiation is now just being raked over, and I expect to see some marked improvements in the near future in the matter of improving the efficiency of electric lighting along the lines of selective radiation rather than from high temperature of materials showing low vapor-tension.

C. W. Hogan: Some time ago my attention was called to a new form of carbon filament, in which an efficiency of 2.5 watts per candle-power was claimed, with an increased life over our present form. I was afterward told that this was due to the cross-section of the filament, and I then made some calculations concerning the difference between the triangular and the circular cross-section. The triangular filament of 5 mils per side is compared with the circular filament having a diameter of 5 mils. In the triangular filament the section is 10,825, and in the circular, 19.66 sq. mils. With the same radiating surface it will give a length of 9.8 for the triangular, and 9.33 for the circular filament. With the same specific resistance, it will give resistance of one inch of carbon, for triangular 147.8, and for circular, 81.4 ohms. The final efficiency figured for 16 c-p., using the same method of treatment for the same carbon material, would be 1.74 watts per candle-power for the triangular section against 3.31 for the circular section.

I should like to know if there is anything in the nature of the carbon which would render these figures void; that is, if the current density will be as uniform throughout the triangular cross-section as it is in the circular cross-section. The amperes for that efficiency would be in the triangular cross-section 0.253 and for the circular section 0.482, so that the carbon would actually be carrying less current in the triangular section than in the circular section. Consequently, it would be at a lower temperature, and having a greater radiating surface the life would be longer owing to the lower temperatures at which the carbon would be operated. And the total illumination from the triangular section would be greater, as there would be more radiating surface for the light.

Charles P. Steinmetz: Answering first the questions raised during the discussion: I also observed the tarnishing of iron in a vacuum, when trying to use iron in the mercury arc lamp. Even in a very high vacuum, iron when heated shows the rainbow colors. I found, however, that even in a very high vacuum, if the mercury arc was started and the space so heated from the inside, remarkably large quantities of gas were given off by the glass walls, etc., and to get a reasonably perfect vacuum it is necessary not only to get a very high grade mercury pump, to have only solid glass connections between the mercury pump and the vacuum tube, but to heat the tube by a heating chamber to a temperature just below where the glass sucks in and keep it at that temperature for hours with the pump working. Then you get a good vacuum, usually, but not always. I consider it possible, therefore, that residual gas, absorbed and tenaciously held by the glass walls, may gradually be given off and affect the iron or other metal.

As to the non-luminous silicon arc, and the production of a very brilliant gas flame by silicon distributed through it, this is a question of comparison. The intrinsic brilliancy of a gas flame is so very low compared with that of a luminous arc, that incandescent silica in the gas flame may appear very brilliant compared with an ordinary gas flame, while compared with a titanium or calcium arc flame, it would have to be called non-luminous.

In regard to 3200° cent. as the melting point of tungsten: 3200° cent. is the black-body temperature of melting tungsten, that is, the temperature which melting tungsten would have if its radiation were that of a black body, but if, as it is very probable, the radiation of tungsten is not that of a black body, the true temperature of the melting point is lower than 3200° cent.

The manufacture of tungsten lamps would possibly be simplified if the metal could be made ductile. I must draw your attention to one feature, however: of all the incandescent filaments, the only one not suited for alternating current is the ductile tantalum filament, which shows a feature similar to the crystallization of wrought iron under rapidly oscillating stress, while the osmium and carbon filaments, which have no fibrous structure, show no inferiority with alternating current. It appears to me possible, therefore, that a ductile tungsten filament may be unsuitable for alternating current.

It is undoubtedly true that the increased surface of the triangular section radiates more light. Unfortunately, it also radiates in the same proportion more heat rays and more total radiation; that means the efficiency would be no better than in the case of the round filament, and the only difference would be that the total radiation from a triangular filament would be greater than the total radiation from a round filament of the same section, and therefore to maintain the same temperature of the triangular filament would require more energy input. The same would be the case by using a hollow filament, but no gain in efficiency results.

Like many other interesting things, the fluorescent cathode-ray lamp has been tried in by gone years by Edison; an exhausted glass tube, coated on the inside with calcium tungstate crystals gave a beautiful white glow. I saw it in operation, but I understand that the difficulty was that the luminescence excited by the cathode rays is excited by an extremely high velocity bombardment, and the impact of this extremely high velocity does not only give light, but gives mechanical fracture and destruction of the fluorescent crystals, and so limits the life of the lamp.

As to the discussion of the various illuminants. We are living in a remarkable time. A few years ago we had the incandescent lamp which as commonly used for series lighting of streets etc., looked somewhat like a red-hot hairpin, which you could see to steer by, just like a beacon light on the river; you could see the light, but you could not see anything with the light. There also was the arc lamp: a big blotch of light, when you were under it you did not see anything, but were blinded by it, and before you came under it you could not see beyond it, and after you left the light you could not see anything at all.

The incandescent lamp has now been redeemed. It promises an efficiency of one watt per candle-power. That means it is superior to the ordinary carbon arc lamp; and possibly you may go still higher in efficiency: the maximum efficiency of light given by a tungsten filament at the temperature of self-destruction is something like 0.2 watt per c. p.; that is, if you run a tungsten lamp up in voltage the efficiency rises to something like 0.2 of one watt per c-p. at the moment where the filaments melt: that is the efficiency at the melting point of tungsten. This efficiency has been beaten by the flame carbon arc lamps and by the different types of titanium arcs. At the same time, the arc is a larger size illuminant. The incandescent lamp has the advantage of giving better distribution of light by smaller units; but the tungsten filament does not have this advantage as much as the carbon filament, because at least at the voltage of 110, it cannot be brought down to the same small units as can the carbon incandescent lamp. This means that very high efficiencies, undreamed of a few years ago have been reached, and the race is still on between the arc and the incandescent lamp. There are future developments possible also in increasing the efficiency of the arc lamp, because even an efficiency of ¼ of a watt per c-p. is ridiculously low compared with the efficiency of the electric motor. However, what is wanted is not light, but illumination, and in the problem of illumination the distribution of light is of importance also, besides the total volume of light. In this respect the smaller size of units gives an advantage to the incandescent lamp. Again, high intrinsic brilliancy is a disadvantage; and low intrinsic brilliancy, that is, large light-giving surface, preferable. In that respect the advantage is with the mercury arc and the vacuum tube and against the ordinary arc, and also against the high efficiency incandescent lamp.

Furthermore, the specific physiological effects of the different colors of light also enter as essential factors, and this is a feature which never had to be considered before, because until the last few years all artificial illuminants gave about the same color, varying from an orange-red to yellow and yellowish-white, while at present you have the bluish-green of the mercury arc, the monochromatic yellow of the calcium spectrum, the white of the titanium arc and so get different colors of light, and the difference of the physiological effect of different colors thus requires consideration.

I stated in my paper, for instance, that green is a much more efficient color than red, and that the same amount of energy as green light gives many more candle-power than as red light; that is, the light-equivalent of energy is a function of the color. It is, however, not only a function of the color, but also a function of the total intensity. The relative sensitiveness of the eye for lights of different colors varies with the absolute value of the illumination. The difference of the sensitiveness of the eye for red light and for green light is many times greater at very low than at high intensity of light. Or, in other words, the physiological effect of lights of different color does not seem to follow the law of inverse squares of the distance, but varies faster than the square of the distance with red, slower with green light. That is, if for instance you have a yellow flame carbon arc and a green mercury arc, which at 100 feet distance gives about the same illumination; that is, appear to the eye as of the same intensity, than at ten feet distance from the light, the yellow light appears far more intense, is glaring, while you are disappointed in the green light. Again, at 1,000 feet distance, the green light appears far brighter than the yellow, and gains over the yellow; the farther away you go from the light, and when the orange yellow light has faded away as a faint star, the green light still throws its visible beam across the darkness. Therefore, where a low intrinsic brilliancy is desired, as in suburban lighting, there the green, irrespective of the physical efficiency, has a great advantage over the reddish-yellow. The reverse applies where very high intensity is desired, a glare of light to draw attention for advertising purposes. Then the reddish yellow is always preferred. These physiological effects of different colors did not receive consideration in former times, but well deserve careful study now, where efficient illuminants of such widely different colors are available, as the flame carbon and the mercury arc.

Wm. J. Hammer: If we go back to the first efforts made by inventors in the field of incandescent lighting, we will find that they were mainly devoted to metal filaments, metallic oxides, and rare earths. Subsequently, the pendulum swung in the other direction, and with the development and perfection of the carbon-filament lamp, attention was concentrated upon that. With the exception of a few inventors, work on the metallic filament was at a standstill. Now the pendulum has swung to its original position and we are having this remarkable development in the metal-filament lamp, which bids fair to displace the carbon-filament lamp; but who shall say that perhaps later the pendulum will not again swing in the other direction? Thus does history repeat itself.

About ten years ago two patents were issued on molybdenum, tungsten, and other metals in which a heated "fillet" of platinum or carbon was placed in a receptacle and oxychlorides in the form of heavy gases were allowed to descend from the top of the containing globe while hydrogen gas, which is very light, was allowed to ascend depositing the metal in a pure state upon the fillet or core. A number of lamps were made, some of which are said to have lasted several hundred hours. No commercial incandescent lamp was made in this way, for the reason that the experimenter did not have the proper fillet of platinum, or carbon on which to deposit the pure metal. It was impossible to obtain a fillet of sufficiently attenuated character to give a commercial lamp; and in the second place, while some of the lamps lasted several hundred hours they soon became black and could not be used as illuminating agents.

Mr. Howell regrets that nothing had been done on this side of the water in connection with this new development. I wish to take issue with him. The foreigners have certainly been doing some very excellent work, but we have with us to-night an American inventor whose work dates back to the time when he was a pupil in Philadelphia, and he has ever since been working on rare metals and metallic filaments.

Reference has been made to the work of Professors Waidner and Burgess of the Bureau of Standards which appears in the *Electrical World* of November 10, and Dr. Steinmetz speaks of the practicability of limiting the temperature of filaments to about 1800°, on account of disintegration; but it is interesting to call attention to the fact that the Heany tungsten which was prepared for the Bureau of Standards in Washington, according to the statements in the report referred to, showed the highest melting point of anything tested. The temperature was 3200° cent., and this was without any appreciable discoloration of the glass globe.

Other inventors using the carbon filament (practically the fillet already cited) heated it in the presence of oxyhalogen compounds, and also in the presence of hydrogen gas, and asserted that pure metallic tungsten was deposited upon the filament. Those who have had experience with tungsten know that it has a great affinity for carbon, and when once united with carbon forms a carbide, and the melting point drops below that of the tungsten itself, which is a great disadvantage. As Dr. Sharp says in his paper, that method seems to be a practical development of the method shown in patents about ten years ago.

SELECTIVE RADIATION

William S. Franklin (by letter): When a given substance is in thermal equilibrium at a given temperature, and surrounded on all sides by substances also in thermal equilibrium and at the same temperature, then the radiation from the given substance is what we call the normal or black-body radiation corresponding to that temperature and the composition of this radiation; that is, the relative intensities of its various wave-length components, is a function of the temperature only and independent of the nature of the given substance. The radiation consists, however, of three parts; namely,

a. The part which is reflected by the substance,

b. The part which is transmitted by the substance from behind,

c. The part emitted by the substance.

If the given substance were opaque and if it did not reflect, it would be called an ideal black body and it would emit normal radiation; and if it were heated to a given temperature in the open it would continue to emit the normal radiation corresponding to that temperature, on the assumption that its molecular condition remains still the same as that which constitutes complete thermal equilibrium.

If the given substance transmits or reflects certain wave-lengths in excess of others then it must, when it is in thermal equilibrium, emit certain other wave-lengths in excess (since the total radiation must be normal when the substance is surrounded by substances at the same temperature), and it is said to exhibit selective emission or selective radiation as it is usually called. Such a substance, when heated to a given temperature in the open, would emit a characteristic abnormal radiation on the assumption that its condition remains still the same as that which constitutes complete thermal equilibrium.

Thus, in brief, we have a sketch of the fundamental idea of selective radiation in the form in which this idea is established in the thermodynamic treatment of radiation.

My remarks on Dr. Steinmetz's paper were intended to point out the fact that the idea of selective radiation, as this term is used by Dr. Steinmetz and by every other writer on radiation so far as I know, contains an idea which is entirely foreign to and incompatible with the narrow thermodynamic idea of selective radiation which is outlined above, and that this foreign idea is of extreme importance in the problem of the production of light.

Selective Excitation

Nearly every one knows that a serious inconsistency has for a long time confronted the physicist in the kinetic theory of gases, in that each of the various modes of molecular motion does not represent the same amount of energy, whereas each possible mode of molecular motion should represent the same amount of energy according to the kinetic theory.

This difficulty has quite recently been explained by Professor Jeans, now of Princeton University, on the hypothesis that it takes time, and in some cases a very long time, for energy which is imparted to a gas as a particular mode of motion to become properly partitioned among all of the possible modes or, if a particular mode is very prone to produce ether waves, and thus lose its energy rapidly, its energy may fall far below normal on account of the slowness with which the store of energy of the other modes is shared by the particular mode as it loses energy by radiation.

Thus in a gas the energy of intra-molecular motion seems in certain cases to radiate rapidly, and in a radiating gas the intra-molecular energy is below par while; on the other hand, a gas which is heated by compression in a closed cylinder has energy imparted to it as increased translational motion and, according to Jeans, it may take a very long time for this translational energy to hammer itself, as it were, into the molecule by repeated collisions.

The indications are that the rapidity with which the energy of a particular mode of motion spreads among the various possible modes in any substance, solid, liquid, or gaseous, is a function of the temperature (if I may use the word temperature in a slightly inaccurate way), and that the spreading is rapid at high temperatures and slow at low temperatures.

To show the application of Jean's idea to radiation, let us consider a hypothetical case, a substance to which energy is imparted predominantly in those modes which correspond to luminous radiation, or in those modes which quickly share their energy with the luminous modes. In such a case the radiation from the substance would be predominantly luminous radiation if the spreading of energy into the non-luminous modes is not too rapid, that is, if the temperature is not too high; whereas if the spreading of the energy among the various modes is accelerated by rise of temperature the radiation would tend to include more and more of all the characteristic wave-lengths of the substance. If the spreading of energy were infinitely rapid, the substance would be in a condition approaching the state of thermal equilibrium, and its radiation would be called its selective radiation in the proper restricted sense of this term.

It seems to me that the giving of energy to a substance predominantly in the form of certain modes of motion might be called selective excitation

I wish in particular to emphasize the clear insight which Jeans' idea, as applied to radiation, gives to several remarkable facts which Dr. Steinmetz points out. The mercury-arc spectrum for example contains no red lines of appreciable intensity when the vapor in the arc is relatively cool, whereas the spectrum becomes greatly strengthened in the red and perhaps also in the infra-red if the vapor is very hot; the energy imparted to the vapor selectively by the (presumably) highly particularized mode of motion which constitutes current conduction, is spread rapidly among the various modes when the arc is hot, and only a small portion of it is radiated in the original modes. The slowness of spreading of energy among the modes of motion, even of solid and liquid substances, is shown by the phenomena of fluorescence, phosphorescence, and luminescence of solids and liquids, and also, I think, by the fact that many substances when bombarded by cathode rays emit line or band-spectra. Furthermore the remarkable band-spectra of absorption of didymium salts seem to show a slow spreading of energy into or out of the didymium atom.

The great retardation of the spreading of energy at very low temperature is shown by the fluorescence at liquid-air temperatures of many substances which do not fluoresce at ordinary temperatures.

I agree completely with Dr. Steinmetz in his statement that theoretically there is no limit to the light efficiency of a luminescent vapor, only I would go further and say that there is no limit to the light efficiency of a luminescent substance of any kind solid, liquid, or gaseous, and I would also be inclined to define the term luminescence as radiation under selective excitation.

The reason that there is no limit to the light efficiency of radiation of a substance under selective excitation, is that mechanical energy (as opposed to heat energy) may conceivably be delivered to a substance in a single mode of motion, whereas heat energy cannot conceivably be delivered to a substance in a single mode. Thus an example is given above of the delivery of energy (mechanical) to a gas as increased translational energy only, in the case of compression of a gas in a cylinder, and such mechanical energy of course spreads out more or less rapidly among all possible modes, and eventually becomes heat energy. It is quite remarkable, however, that energy imparted to a gas by compression seems to spread out with extreme rapidity among such modes as play a part in the determination of the specific heat of the gas (as shown by the close correspondence between the calculated ratio of the specific heats at constant volume and at constant pressure of a biatomic gas, and the ratio as determined by methods involving quick expansion such as the method of Clement and Desormes), while the energy is spread into the other modes with excessive slowness.

I believe that the idea of Jeans is destined to play an important role in the theory of radiation from substances not in thermal equilibrium—which indeed is the only actual existent case of radiation.

Consider the Welsbach mantle for example. We know that its spectrum is abnormal; that is, it departs very widely from ideal black-body radiation. Is it likely that this abnormal radiation is a genuine case of selective radiation in the restricted sense of that term, that is to say, is it likely that the hot substance of the mantle presents all of its possible modes of molecular motion in approximately the relative intensities which correspond to thermal equilibrium and that the abnormal radiation is due to a natural preponderance in this substance of certain modes which jar the ether so as to produce luminous radiations, or is it likely that the abnormal radiation is due to selective excitation and a consequent wide departure of the hot substance from the condition of thermal equilibrium? It is impossible to say.

Energy is of course imparted to the mantle by the highly disordered movements of combustion, but surely these movements must be very far removed from the type of molecular motion which constitutes thermal equilibrium. That is to say, the possibilty exists of a marked degree of selective excitation of the substance of the mantle and it seems to me that there is too much of a tendency to think of the abnormal radiation of the Welsbach mantle as an inherent property of the mantle (abnormal radiation due to selective radiation proper is due to an inherent property of a substance; abnormal radiation due to selective excitation depends of course to some extent upon inherent properties of a substance, but also it depends quite as much upon the character of the selective excitation) whereas it may be a mutual property of the mantle material and the particular kind of combustion which is employed to heat the mantle.

Consider the ordinary glow-lamp. Here we have unlimited possibility of selective excitation because the motion which constitutes the electric current is probably a highly particularized mode of motion. The approximately normal radiation from a glow-lamp seems to show an extreme rapidity of spreading of energy among the various modes of the solid substance of the filament.

In the case of a vapor-lamp we have perhaps something like the same kind of excitation as in a solid-filament lamp, but a very much slower spreading of energy, especially if the vapor is relatively cool, and as a result we have an extremely abnormal radiation.

In the firefly, or indeed in slowly burning phosphorus, we most certainly have a strongly marked case of selective excitation coupled with a comparatively slow spreading of energy.

A paper presented at a Meeting of the University of Wisconsin Branch of the American Institute of Electrical Engineers, Madison, Wis., December 20, 1906.

HIGH-TENSION OUTLETS.

BY ALVIN MEYERS.

The building outlet in high-tension work has become very important and will increase in importance as higher pressures are used. A great variety of outlet arrangements have been tried, each company having a method of its own. Each arrangement has its disadvantages and all are liable to give serious trouble in case of storms. Blowing rain and snow will enter the building with the open outlet, while with the bushing it is found impractical to build with glass or porcelain to sufficient size to obtain the necessary surface resistance. Plate glass with holes through the center for the wires, which are supported on line insulators, has proved a serious menace, owing to the leakage setting fire to timber construction, and the formation of an arc in metal construction.

Inferior designs of outlets have often given fairly good satisfaction, due chiefly to local storm conditions. It is not extremely difficult to provide ample insulation as long as this insulation can be kept thoroughly dry, but when exposed to driving rain and sleet defects appear very quickly. In all cases the outlet insulation should be better than that of the line itself, owing to electrical storms which are otherwise liable to start a disastrous arc at the outlet end of the building.

The early outlets of the Telluride Power Company were of two types—the voltage on the system being 44,000 between lines on a star-connected bank of transformers with the star grounded—the first type (see Figs. 1 and 2) employed at the power house at Nunns, Utah, consisted of a 4 in. by 4 in. oak timber about 5 ft. long with a 1-in. hole bored through the center to carry the wire which was incased in a hard-rubber tube.

The oak was very carefully paraffined, and then passed through a tight-fitting hole in the wooden gable of the power house. On the outside each bushing was further protected by a hood. All of the high-tension gable and the hoods were built with care from seasoned timber, and coated with shellac and varnish. These outlets have given some trouble in the case of a driving storm of snow and sleet from the direction favorable to the wetting of the whole gable-end of the power house.

The second type of outlet was constructed in about the same way, except that the oak bushing was omitted and the line carried through an opening underneath the hood. In this case, snow blowing into the building was probably responsible for arcing over the transformer bushings.

In 1903 a series of tests were made at the Telluride Power Company's laboratory in Provo Canyon, on what was then a new insulating material called fibre conduit. This material is intended for use as underground conduit. It is manufactured in tubes of varying diameters, and in uniform lengths of 5 ft. each, the walls being from ¼ to ½ inch thick. These tubes secure their mechanical rigidity and insulating properties from a fibrous body treated with an asphaltum compound.

Fig. 1.

The results of the tests were as follows:

Walls ¼ in. thick punctures at 34,000 to 36,000 volts.
" ⅜ " " " " 49,000 " 57,000 "

No appreciable deterioration could be detected when the potential was maintained near the breakdown point for 10 hours.

The arc at first seems very loath to hold near the surface of a dry conduit; but after a continued test with constant leakage the arc finally starts and carbonizes a channel when it will hold along the surface. An arc sufficiently violent to carbonize the dry surface causes the material to burn with very little flame, which goes out almost instantly when the current is turned off. *Wet* surfaces deteriorate very rapidly, burning and carbonizing over almost the entire surface. This burning is plainly visible some time before actual breakdown occurs, and begins at a point so low as compared with dry surface tests that it was difficult to make any comparison, especially as the amount of moisture and the rapidity with which the test piece dried off after being soaked, was quite variable.

A bushing was next built up, as shown in Fig. 3. This bushing was built of three straight lengths of fibre conduit; 1½-in., 2½-in., and 4-in. tubes being placed concentrically, the spaces being filled with ozokerite. The outer end consisted of a 4-in. *T*-joint capped on the upper end and fitted with a 6-in. nipple on the lower end, this latter serving as a petticoat. A rubber-covered No. 8 flexible lead through the bushing was made one terminal of the transformer, the other terminal was

Fig. 2.

wrapped around the bushing at approximately what would be the wall position for such bushing. With this arrangement, 64,000 volts and upwards was applied for over five days, and although there appeared to be considerable radiation from the wires no surface leakage could be detected. Later the voltage was raised to 110,000 when light arcs and streamers over the end of the bushing inside of the transformer house indicated that the limit of surface resistance was reached, but no burning or puncture was obtained.

For the purpose of making the wet test, a hose with river water was set playing against the gable of the transformer house above the bushing. This threw a heavy spray over that part of the bushing outside the transformer house. First, the hose was left playing for two hours; then the pressure was raised in about 5 seconds from 0 to 48,000 volts when a heavy arc formed across the 4-in. air-gap at the end of the bushing, thence along the surface to the wire wrapping. The pressure was instantly taken off and after drying for 10 to 15 minutes (the atmosphere was very dry with some wind) the pressure was again applied without the hose being turned on, and the bushing stood up

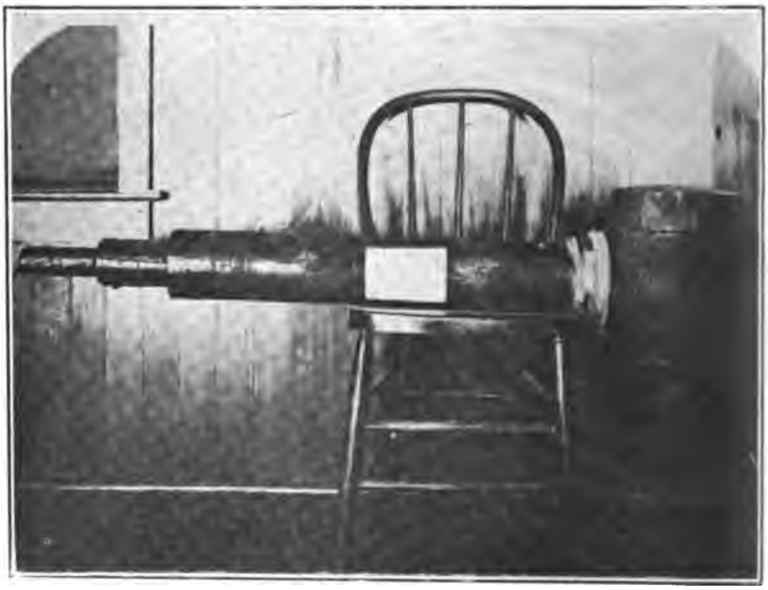


FIG. 3.

under 64,000 volts. An examination showed no appreciable carbonization. Next the hose was turned on again and the pressure raised more gradually with readings of voltmeter and wattmeter taken on the low-tension side. Excessive burning over the bushing surface became visible at 30,500 volts, but the wattmeter reading showed excessive loss starting at 22,000 to 23,000 volts. Finally the bushing was severely burned on the surface by allowing a heavy arc to hold for several minutes while the hose was playing. This caused a carbonized channel to be formed about 2 ft. in length along a rather erratic path, not zigzag, but not the shortest path. The channel was about $\frac{1}{16}$ in. deep. All this carbonized material was carefully scraped off and the dry test showed the bushings to be as good as ever, while the wet test was repeated with approximately the same results as before. The bushing was left in place during the progress of some other tests, and has since been subjected to an actual storm test of wet snow and snow and rain mixed, with considerable wind, lasting for about 48 hours.

An actual storm test confirms the test with hose and spray of river water, and the wet tests as a whole show that the surface resistance of the conduit may be reduced 80% by wetting, while the puncture test remains practically the same with dry as with wet surface. A dry surface test compares favorably with a dry surface test on insulator glass. The puncture test shows excellent insulating qualities.

From the tests it will be seen that this material has properties that make it, when exposed to the weather, an unsuitable material; that is, its surface insulation when wet is very poor, while its dry surface and puncturing resistances are very good. Numerous varnishes and like materials were used in the endeavor to protect the exposed surface, but without results of sufficient value to warrant the use of this bushing exposed to weather conditions.

In the design of the Olmsted power house outlets, see Fig. 4, it was decided to make use of the fibre conduit with the ozokerite filling. The bushings are filled chiefly with crude ozokerite, while the ends are sealed for short consecutive spaces with chatterton compound, minerallac, and a very brittle asphaltum compound. These were used to prevent the oozing out of the material when subjected to the heat of the sun in summer. The chatterton compound has proved to be less firm than the others and has oozed out slightly.

In order that the exterior surface of these bushings might be kept dry, a sheet-iron hood was designed to protect them from storms. See Fig. 5. The bushings were made of considerable length in order to decrease the surface leakage.

The conductor in these bushings is insulated for 60,000 volts with varnished cambric and braid, and is just large enough to fill tightly the 1½ in. inner tube of fibre conduit. These bushings have proved quite satisfactory, but it must be noted that the hood provides excellent protection against storms.

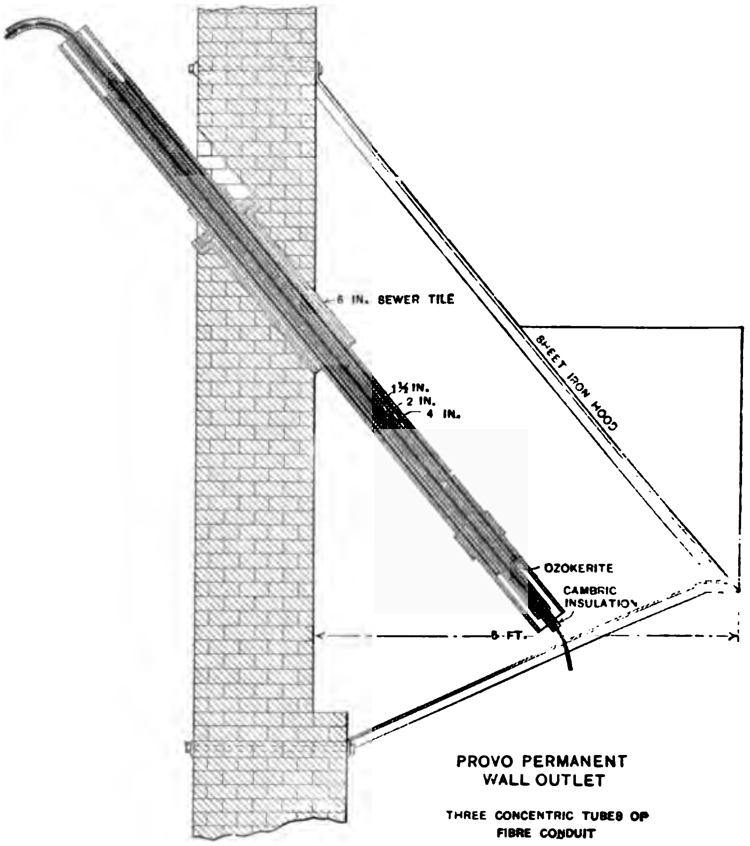


Fig. 4.

Tests on the 1.5 in. conduit with the insulated conductor alone gave a breakdown by puncture at 112,000 volts at the end of one minute's application.

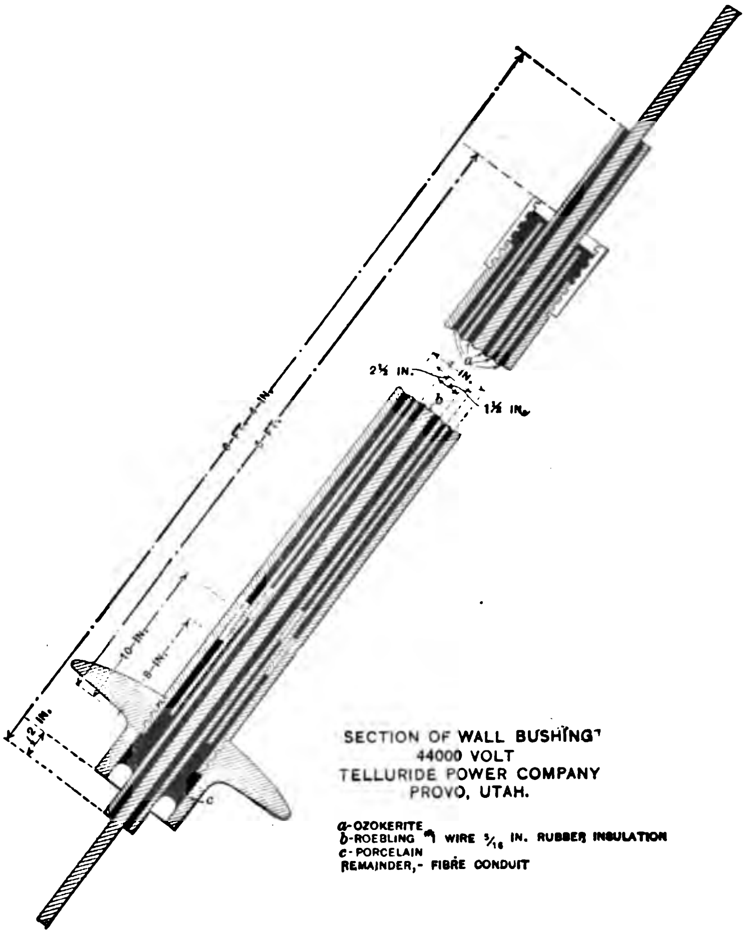
Later in the spring of 1905, a switching station near Lehi, Utah, was equipped with approximately the same style of bushing, 40,000-volt insulated wire being substituted for the 60,000-volt wire mentioned above. It was thought that a liberal roof projection on the building would protect the surface of these bushings and they were set in the wall in a much more nearly horizontal position than at Olmsted.

These bushings had been installed but a short time when all nine were practically destroyed during a driving rain storm accompanied by lightning. Several were punctured and the rest were severely burned over the exterior surface. This switching station is located in an unprotected place, where it is subject to the full force of storms as they come across Utah Lake.

Fig. 5.—Power House at Olmsted, Utah.
10,000 h.p. capacity; line pressure 44,000 volts.

In consideration of the necessity of further protecting bushings of this kind from surface breakdown a porcelain collar was designed to screw on to the threaded end of the 4-in. conduit. See Fig. 6. Before screwing this collar on to the conduit, hot ozokerite wax was poured over the threaded end of the conduit for a few minutes. A warmed collar was then quickly screwed home.

In December 1905 a switching station with twelve of these bushings with porcelain collars was installed near Ogden, Utah, the building in this case furnishing protection by a projecting roof. Thus far this arrangement has proved satisfactory.



SECTION OF WALL BUSHING
44000 VOLT
TELLURIDE POWER COMPANY
PROVO, UTAH.

a-OZOKERITE
b-ROEBLING #1 WIRE 5/16 IN. RUBBER INSULATION
c-PORCELAIN
REMAINDER,- FIBRE CONDUIT

FIG. 6.

Tests at the laboratories with the bushings equipped with the porcelain collars showed the weak point to be between the collar and the conduit. Dry and wet tests alike broke down between the porcelain and the threaded surface at 97,000 to 104,000 volts. This would indicate that this bushing was likely to give fairly good results even if exposed to the weather, since as far as all line conditions are concerned there would be no danger of breakdown at the normal line pressure or at any voltage that might be caused by switching, since a pair of these bushings would break down at about 200,000 volts. It must be remembered, however, that a lightning storm might easily produce a potential from line to ground that would break down one bushing alone at half this voltage, and this is the condition to be feared. Further tests on this style of bushing show that the whole series of tubes is likely to puncture at about 120,000 to 130,000 volts.

In further pursuing this work for the Telluride Power Company, the writer has endeavored during the past winter to produce a bushing which could be built and installed so as to obtain the following desirable features which are not obtained by other designs:

1. To design a bushing one end of which might be directly exposed to the weather, thus doing away with the necessity of a hood protection which is not only expensive but has been itself the occasion for disaster in the case of severe wind storms which have in several instances torn away the hoods, together with the lines, and parts or all of the buildings.
2. To design a bushing that might be adapted to the roofs of buildings so that lines could be kept sufficiently far from the ground with less height of walls and consequently less expense in building small sub-stations, etc.
3. To design a bushing of such insulating strength that even a building of the cheapest sheet-iron construction could be used for a sub-station in an outlying district, without danger from breakdown by puncture.
4. To design a bushing which would cost far less in both material and labor than the forms previously used.

To accomplish the first object it was thought advisable to get some reliable insulator which might be so combined with the fibre conduit that the exposed surface insulation of the conduit would not be relied upon at all. To do this it was thought that if an ordinary high-tension insulator having sufficient insulating surface to make it adaptable to an iron pin could be cemented to the conduit this part of the problem could be solved.

Further, the Telluride Power Company secured some refined ozokerite which showed remarkable insulating properties.

This material as received was a black wax melting at 150° cent., and although it can be readily broken with a sharp blow when cold, it remains quite tough and slightly pliable when subjected to a steady strain even at 0° cent. An electrical test of this material was prepared by moulding plates about ½ in. thick into each side of which, before cooling, circular lead punchings were pressed with a pair of calipers until the distance between the lead discs was $\frac{3}{16}$ of an inch. The discs were then used as terminals, and the voltage required to puncture was from 120,000 to 130,000 volts.

In looking over the different insulators on hand, a dozen multipiece insulators were found which had been tested by the writer in 1903. These insulators were found to form a good combination for uniting with the fibre conduit. See Figs. 7 and 8. It was decided to use a base and one intermediate petticoat piece of this insulator as shown in Fig. 7, depending upon the ozokerite filling to seal the connection between the conduit and the glass. It was found that much greater mechanical strength, that is, better adherence between the glass and ozokerite was obtained by painting the inside of the insulator with a solution of ozokerite dissolved in gasoline, before pouring the hot ozokerite upon the glass.

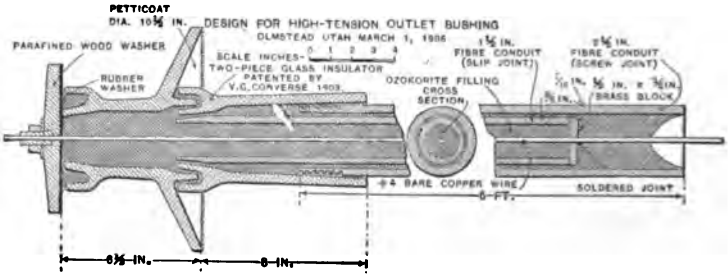


FIG. 7.

In the above arrangment the adaption of the bushing to a roof outlet is easily accomplished by using a pair of wood clamps to hold the bushing directly upon the ridge of the building. The opening between the clamps and around the bushing could be filled with ozokerite wax and the clamp blocks then bedded in a mortar of plaster of Paris mixed with plastering hair, and then bolted to the roof.

To improve the insulating qualities so as to make the bushing secure from puncture when placed through a sheet-iron roof, ozokerite was again considered on account of the insulating properties before noted.

On filling all previous bushings it was noticed that the ozokerite seemed to boil and froth considerably when poured into the conduit. Numerous tests were made of the puncturing voltages on bushings filled in the simplest manner. From these tests it was found that actual air-holes were left in the ozokerite, and the puncturing resistance was seldom increased by so filling. This led to an effort to fill the conduit so as to insure a solid mass of ozokerite, anticipating that if this could be accomplished the puncturing resistance would be increased many times.

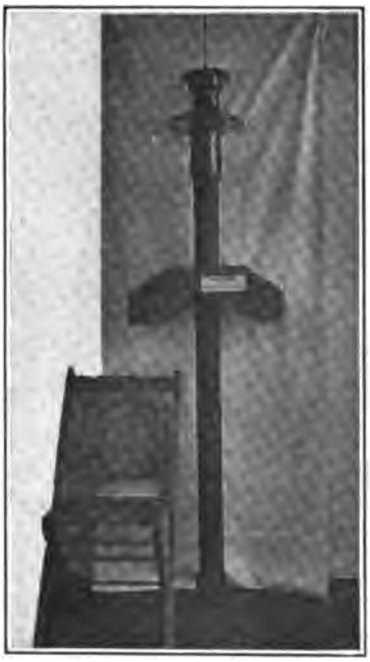


Fig. 8.

In the attempts to insure this homogenous condition of the ozokerite the following experiments were tried: pouring at different temperatures; kiln-drying the conduit; rinsing out the conduit with hot ozokerite before filling, pouring and stirring, and lining the interior of the conduit with heavy brown draughting paper. The latter was finally found to give success after rinsing out with hot ozokerite, or rather filling and then emptying and refilling after heat had driven all froth off the material that had been used in rinsing. The pouring was finally done very slowly, only a foot or so at a time with half-hour intervals, owing to the extreme contraction of the ozokerite in cooling. This procedure kept the top part always hot so that it could sink down as it cooled from the bottom. Several pieces of ½-in. conduit were thus built up with a wire through the center, and the voltage applied to cause puncture reached 140,000 volts and over, while the conduit alone punctured at 49,000 to 57,000 volts.

It should be stated that much labor was thrown away by a burnt lot of ozokerite which was finally discovered by attempting to chew samples both of the material used and of fresh wax. The burnt material would crumble in the mouth and could not be formed into a gum, while the fresh wax would form a tough gum.

With the experience gained from these tests, and the objects before mentioned in view, a complete bushing was now built up according to the following:

SPECIFICATIONS FOR CONSTRUCTING AND INSTALLING 44,000-VOLT OUTLET BUSHINGS.

Constructing. Take a petticoat piece and one base of an insulator, as shown in Fig. 7, clean them carefully and paint the interior surfaces with a solution of ozokerite wax dissolved in gasoline. Place both pieces upon a radiator, or make some similar condition where the glass may be warmed up slowly, finally attaining a temperature of from 150 to 200° fahr.

Prepare a piece of 1½ in. conduit, 5 ft. long, by rolling a piece of heavy brown draughting paper 7 in. wide by 5 ft. long upon a round stick or piece of pipe and insert the paper into the conduit; then let the paper spring out and withdraw the form. Heat some of the ozokerite until thoroughly fluid and free from froth and fill the conduit. A wooden plug held by a thumbtack is sufficient to close one end while filling. When full, empty the conduit (saving the ozokerite for final filling) and place it into a form to hold it straight. A straight piece of plank with a few cleats and screws will serve for this purpose.

The wire should be of bare copper of the size desired, with a ½ in. threaded brass sleeve 1½ in. long soldered 6 in. from one end. Pass the wire through the prepared conduit. A wood block 2 in. in diameter, 1 in. thick with a hole in the center should then be slipped over the free end of the wire, and a brass wire connector should be clamped or soldered back of the block so that it will pull the block against the conduit, when the threaded sleeve is 6 in. beyond the other end of the conduit. By using a threaded nut on the brass sleeve and drawing against some stays upon the form, the wire may now be firmly tightened and drawn centrally within the conduit.

With the conduit in the form and ozokerite in good fluid state and free from froth, begin pouring, the conduit being inclined about 60° with the horizontal. First fill the first 2 ft. and then fill a foot at a time at intervals of about one half hour. Longer intervals should be used in hot weather. Keep the wire tight; heat will loosen it.

When filled and cold, wrap the conduit with wire (or tin foil) using wires about 1 in. apart to within about 14 in. of either end. With the wrapping as one terminal of the testing transformer, and the central wire as the other terminal, raise the voltage slowly up to 120,000 volts.

If the test is without puncture, remove the form and slip the base of the warm insulator over one end—the end may have to be shaved down slightly to make it enter the insulator with a good fit. Slip a piece of 2½ in. conduit over the other end to within a few inches of the glass. Then fill the base of the glass with ozokerite (not too hot) and slip the 2½ in. piece of conduit into the hot wax as far as possible: it should enter an inch beyond the threads at least. After a few moments for cooling, stand the bushing upon the lower end and put on and fill the petticoat insulator piece, lifting it quickly before the ozokerite cools just sufficient to let the ozokerite run into the joint between the two glass pieces. In filling the glasses, care should be taken not to have the ozokerite extremely hot but in a thoroughly fluid condition. The pouring should be done continuously but slowly.

When the material in the insulator has cooled, turn the bushing upside down and fill between the 2½ in. and the 1½ in. conduit pieces with ozokerite. When this has cooled, test for puncture again, wrapping the whole bushing from the glass to within 14 in. of the lower end with a wire for one transformer terminal and the central wire of the bushing for the other terminal. Bring the voltage up slowly to 120,000 volts as before.

If the test does not puncture it shows that the filling of ozokerite has been successful and the bushing will probably require something over 170,000 volts to puncture; since the 2½ in. conduit alone has an insulation resistance of about 50,000 volts. If the inner tube has received a blow or mechanical injury when cold and before being supported mechanically by the 2½ in. outer tube, the two will break down at about 80,000 volts.

After this test, the cap and gasket may be put on top of the insulator and securely fastened by using a ½ in. nut and cut washer.

A pair of clamps should now be made of two 4 in. by 8 in. timbers each about 20 in. long, and bolted to the bushing 1 ft. below the glass insulator. Clamps should be sawed to fit the pitch of the roof so that when fastened to the bushing the slot between the clamps may be filled with ozokerite so as to make them water tight. Several coats of good paint should be applied to the clamps to prevent weather-checking. Four ½-in. carriage bolts with nuts and washers long enough to reach through the ends of the clamps and the roof should be supplied with the bushing.

Installing. Each bushing is designed to go directly through the ridge-pole of the building. The sleeve on the lower end of the bushing may be removed and a hole cut through the ridge just large enough to allow the bushing to pass freely through. The bushing should then be set in place and the holes marked for the roof bolts. The bushing is then lifted up and these holes drilled, after which a bed is made of plaster of Paris mixed with hair; the bushing, is then lowered, and the clamp blocks bolted to the roof.

The bushings should be spaced at least 3½ ft. on centers; preferably 4 ft., and like distances should be left between the bushing and the gable-end of the building.

When the bushing is in place the 2½ in. coupling at the lower end should be screwed back and plugged full of plaster of Paris, the purpose being to keep the ozokerite from oozing out.

The bushings are not designed to withstand any appreciable mechanical strain, hence it would be preferable to set a pole on either side of the building to carry the main line over the building, thence dropping short taps to the bushings; or set a

" dead end " pole very close to the buildings so that the span of the bushing may be very short and the wires slack. Ground each bushing with a No. 4 bare wire, about three turns both just above the clamp-blocks and just beneath the roof.

According to the above specifications, one bushing was first built and installed through a sheet-iron roof of the transformer house, and 96,000 to 100,000 volts applied between the ground wrapping and the bushing terminal for about three days during which several severe wet snow storms occurred. A special test made during this storm is shown in Fig. 9.

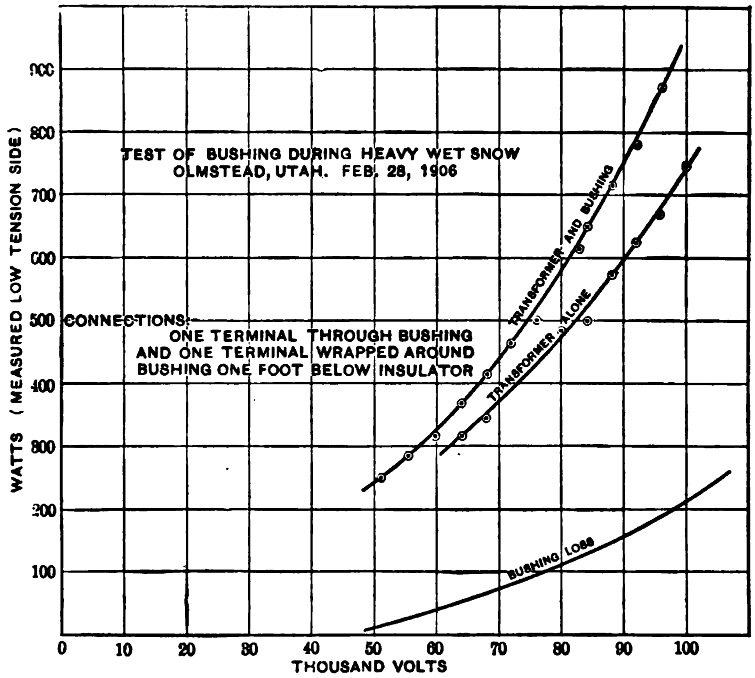


FIG. 9.

After this a voltage of 83,000 was applied to the bushing for over three weeks, with recording instruments on the low-tension side of the transformer recording watts and volts. Although a number of storms, wind and snow, more or less severe, occurred during this time, no appreciable change could be noted on the wattmeter which was sensitive to a difference of about 30 watts.

Shortly after the test of the first bushing, four more were built; three for a small sub-station on the Telluride Power

Company's system, and one to complete the pair of bushings for outlets of the 150,000-volt testing transformer house at Olmsted. The cost of building these bushings is given below:

Cost of Material Used For Three Outlet Bushings.

3 pieces of 2½ in. fibre conduit 5 ft. at 9 cents	$1.35
3 " " 1½ " " " " " " 5 "	0.75
3 " " No. 4 copper wire, each 7 ft. long, 3 lb. at 26c.	0.78
3 insulators consisting of one middle piece and base (estimated) at 27c.	0.81
Three 2½-in. fibre conduit couplings threaded 15 cents	0.45
20 lb. of ozokerite at 7 cents	1.40
1 box tape	0.29
18-½ in. by 9 in. carriage bolts	0.65
6 in. ½-in. brass rod, ½ lb	0.15
2 lb. ⅛ in. rainbow packing, at 66 cents	1.32
36 bd. ft. common lumber	0.83
25 lb. plaster paris	0.16
5 lb. plastering hair, at 2 cents	0.10
Labor, one man 3 days (estimated)	9.00
	$18.04

A true comparison is hard to obtain in regard to the cost of the various styles of outlets that have been mentioned. It is probably a safe estimate to say that in the case of bushings requiring hoods, the hoods alone cost from $12 to $30 per bushing. The bushings at Olmsted station cost $25 each to build, and the cost of hooding per bushing was about $30. The porcelain collared bushings have cost $18 to build, and the hooding may be estimated at $12 each. With the bushing designed and built under the above specifications, it will be seen from the itemized bill that the cost per bushing is about $6.00 while the cost of installation and hooding is practically zero.

All laboratory tests indicate that the electrical properties of the new bushing are far superior to those of other designs. The only questions that may arise are in regard to the durability in service, when the ozokerite is subjected to such temperature and mechanical strains as cannot be avoided.

A paper presented at the 212th Meeting of the American Institute of Electrical Engineers New York, December 28, 1906.

RECENT INVESTIGATION OF LIGHTNING PROTECTIVE APPARATUS.

BY R. P. JACKSON.

Owing to the peculiar nature of lightning and similar disturbances, a variety of opinions continues to exist concerning their action and the usefulness of various devices for protecting against them. In this paper, an attempt is made to outline the most dominant characteristic of lightning as manifested on electric circuits and recent investigation as to what characteristics protective devices should possess and to what degree they have been found in practice to possess them.

While the record of effectiveness of various devices in service is the final test, very misleading results may be still obtained, due to the large factor of chance and accident sure to be encountered, and to the difficulty in ascertaining the actual condition after everything is past. It has sometimes happened that an operator has had the greatest assurance that he obtained protection from a particular arrester, when a little investigation mixed with common sense would show that by no means could the device have done any good.

A MECHANICAL ANALOGY.

In many ways the various characteristics of electric circuits can be represented by mechanical analogies, though no one analogy will hold good for all the phenomena. So, while helpful, caution must be exercised or one will be lead astray. The following analogy is not new, but is especially well fitted to represent the static elements of an electric circuit.

Assume an elastic fluid like a heavy gas having inertia and capable of various states of pressure and motion without changing its characteristics. Enclose this fluid so as to flow in directed paths, such as pipes, and provide pistons, as shown in Fig. 1, one of which may receive power and the other deliver it. If one of these pistons is moved back and forth, the fluid in the pipes is compressed and expanded in turn while the other piston moves a little later in phase and may do work. The amplitude of motion determines the flow of fluid.

Electrically, we may consider that one of these pistons represents a generator and another a translating device, such as a transformer. The ability of the fluid to be compressed and expanded corresponds to the electrostatic capacity of the line, while the inertia and frictional resistance to the motion of the fluid represent respectively the inductance and the resistance of the line.

Choke-coils may be represented by smaller pistons *C*, *C*, of considerable inertia but moving freely in the pipe. It may be noted that the pistons *P*, *P*, which represent the generator and transformer, likewise have inertia but are also moving against the resistance of their load or the work that is being done. Small plugged vents *A*, *A* are the equivalent of the lightning-arresters. The resistance to the flow of fluid through them after the plugs have been ejected corresponds to the series resistance of the arrester, while the security with which the plugs are held represents the length of gap. It is obvious of course that very small holes for vents will give correspondingly little relief in case there should develop a rise of pressure. A larger hole will give a greater degree of relief from excess pressure, and the size of vent necessary to limit the pressure at a given point to any value is dependent on the rapidity with which fluid at any objectional higher pressure can reach the vicinity of the vent. The result

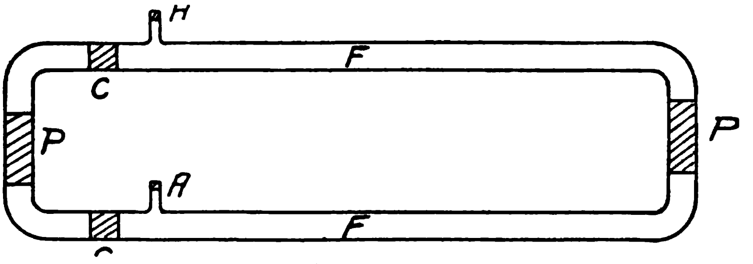


Fig. 1.

of numerous experiments indicates that a true conception of the effect of lightning and other static phenomena, on transformers and generators, is only to be had by considering them as analogous to cases of impact of surges in an elastic fluid.

Suppose we assume in Fig. 1, that an explosion has occurred at some point in the pipe and that this explosion has had the effect of producing for some length of the pipe an immensely increased pressure. This fluid, if retained by the pipe, will expand in each direction with a rapidity controlled mainly by the inertia and elasticity of the fluid. If this wave of high pressure strikes a piston of great inertia an additional rise of pressure and also a reflection of the wave will occur. If we are especially desirous of keeping the pipe from bursting near the piston, or if it happens to be impossible to make the pipe as strong near the piston as elsewhere, there are two devices which serve to relieve the stress at that point. They are indicated in Fig. 1 and operate in different ways.* A loose piston of considerable inertia will reflect part of the wave before it reaches the main power piston and so relieve the strain on the pipe in the vicinity of the latter. Also a suitable vent will permit the escape of sufficient fluid to limit the rise in pressure. How may this analogy be applied to electric circuits?

If a wire becomes inductively charged for a portion of its length by a cloud overhead, and this cloud discharges to ground, a free charge suddenly exists on the wire and at once expands in both directions with about the velocity of light. If this charge escapes at some point through a certain amount of inductance, oscillations will of course be set up. Under proper conditions the elastic fluid assumed in the analogy would act in the same

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*An attempt to make an analogy include all the phenomena of electric circuits leads to burdensome complications. It may be observed that pistons are only suitable to illustrate or represent inductances where the flow of the fluid is considered to be alternating. A true analogue is to assume a heavy pivoted mass like the rotating part of a steam turbine. After such a mass had been set rotating by continuously flowing fluid, it would offer no further impediment to flow, except the incidental frictional resistance, just as inductance acts with continuous current.

If such a mass be equipped with a multitude of small vanes, there will be, while the mass is being accelerated, a difference in pressure from one end to the other, manifested by the fluid driving or accelerating the mass. A heavy surge in the fluid striking the vanes might bend or break some of the first row or circle before the mass could be accelerated. This represents in some degree the breaking down between turns of electrical apparatus.

manner. The probable effect, however, is simply that this charge in expanding strikes the transformer with a terrific impact. The inductance or electrical inertia of the transformer causes the surge to bank up in a manner similar to water-hammer in a pipe. A rise in pressure and partial reflection occurs, dependent in amount on the suddenness of impact or steepness of the wave-front of the surge. It should be noted that though this illustration is used because water-hammer is a familiar phenomena, the analogy is not entirely true inasmuch as water is not so elastic as a gas.

It is the effect above noted that causes the bursting of transformer and circuit-breaker bushings, though their insulation is stronger than that of the line from which the surge comes. The pressure near the transformer terminal is greater, perhaps twice as great as it is at some distance back on the line. Fig. 2 shows what might be an instantaneous condition when *F* represents the line and *P* the transformer winding.

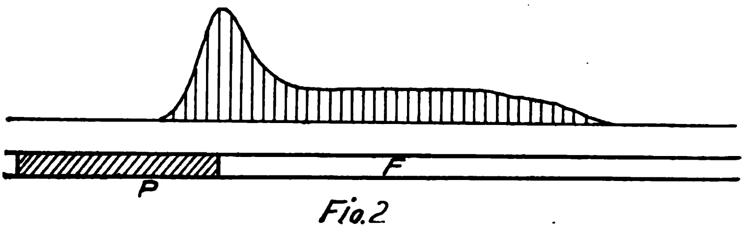

Fig.2

THE CHOKE-COIL.

Now to revert to the analogy, it can be assumed that inertia is represented by the pistons *C C* and there can be inserted its electrical equivalent, an inductance or choke-coil. Apparently a well-insulated choke-coil in the lead of the transformer simply divides this impact into two parts, as shown in Fig. 3. Fig. 3 does not, of course, represent an instantaneous condition, but rather the two maxima with a slight time-interval between. There are, of course, two separate reflections; one from the choke-coil, and one from the transformer winding.

It should be noted that there are two stresses; one from the conductor to ground, the other between different parts of the same conductor. In Fig. 2, there is a large difference of potential between the lead and a point a short distance in on the winding. This is the cause of the breaking down between turns of transformers and generators, one of the commonest manifestations of lightning trouble.

As indicated in Fig. 3, there is for an instant a large difference of potential between the terminals of the choke-coil, and a moment later a condition similar to that in Fig. 3 occurs in the transformer, but to a less degree. The amount of inductance in the choke-coil determines the amount of impact taken up by the coil and the corresponding relief to the transformer.

Fig. 4 shows how these stresses are distributed in a transformer winding. A 30,000-volt transformer winding of 2000 turns had leads brought out every 200 turns. It was arranged to have a condenser of 0.1 microfarad, charged to about 50,000 volts, discharge into and through this transformer. Spark-gaps were placed between adjacent leads, in each case spanning 200 turns. Fig. 4 shows the curve for only half of the transformer winding. Curve *A* shows the rise in pressure across each section when unprotected. Curve *B* shows the result when a choke-coil of 0.0165 henry is placed in the lead. Curve *C* indicates the flattening effect on the potential distortions within the transformer when a choke-coil of 0.1764 henry is used.

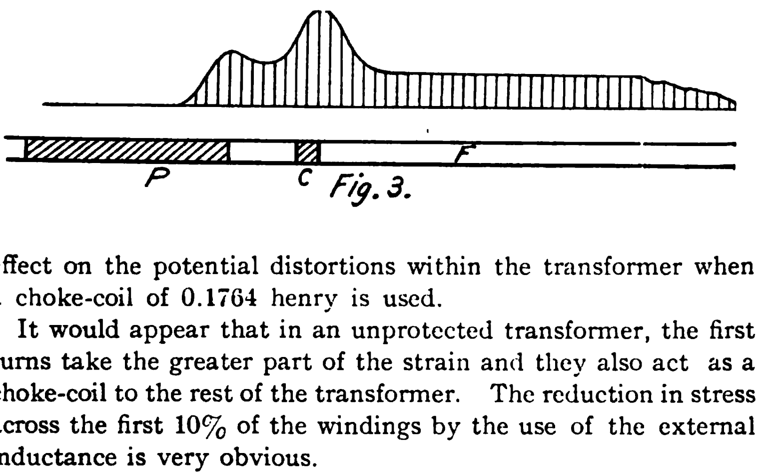

Fig. 3.

It would appear that in an unprotected transformer, the first turns take the greater part of the strain and they also act as a choke-coil to the rest of the transformer. The reduction in stress across the first 10% of the windings by the use of the external inductance is very obvious.

Fig. 5 shows the result on the first 10% of the windings where various inductances from zero to 0.07 henry are used. With no choke-coil, the stress appearing across the leads 1 and 2 is taken at 100%. With the different choke-coils the lower values indicate the per cent. that may still be said to pass through the choke-coils and appear as stresses across the first 200 turns of the transformer windings.

A flatter wave-front would, of course, tend to make Curve *A* Fig. 4 approach Curve *C* and the curve of Fig. 5 would have a lower maximum, but would probably take the same shape; that is, the same coil would permit the same per cent. of the maximum rise in the transformer, independent of the wave-front.

A transformer of different design would also probably give a similar curve, except that for the same surge a different proportion of the windings would be required to give the same rise in pressure. In other words, it does not appear to be a certain per cent. of the transformer winding that receives the shock; but, it is more probable that the first inductance encountered by the surge receives the stress to a certain depth measured from the end of the winding which first receives the blow. If external inductance is inserted, the amount of the stress taken up by it will depend on its amount, all values considered independently of the iron. Therefore a transformer of a very few turns would naturally have such an impact stress distributed over most of its windings, while one of many turns is only endangered in the first small per cent. of its windings. As the inductance of any coil is, in general, proportional to the product of the mean turn and the square of the number of turns, it follows that the larger a transformer is, the better is its inherent insulation against the impact stresses. For example, assume two transformers that at the same frequency will give 25 and 4 volts per turn respectively; presumably one

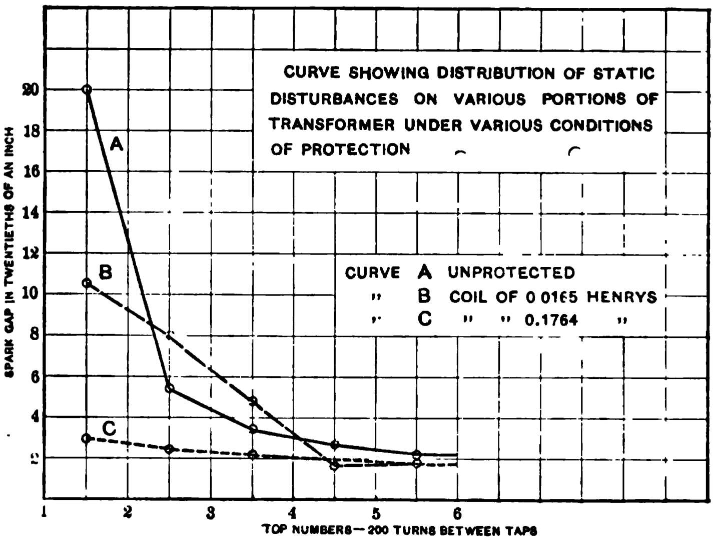

Fig. 4

will have insulation for 1000 volts total between the first 40 turns, while the other will be provided with that amount of insulation only for the first 250 turns. The same inductance encountered in the first 40 turns of the larger transformer will, however, be found in the first 63 turns of the smaller. The insulation of the latter would normally be for only 250 volts, there being only ¼ the number of turns required, for 1000 volts operating potential. Consequently the smaller transformer, while suitably insulated for its operating condition at normal frequency, is not so well protected against surges as the larger one.

In a general way the curve of Fig. 5 is borne out by results from coils in use. Coils of low inductance have in some cases permitted sufficient disturbance to penetrate as to damage the transformers, while the better type of oil-insulated coils have been such good reflectors that the only difficulty has been in maintaining the insulation of the coil itself against the banking up of potential across it.

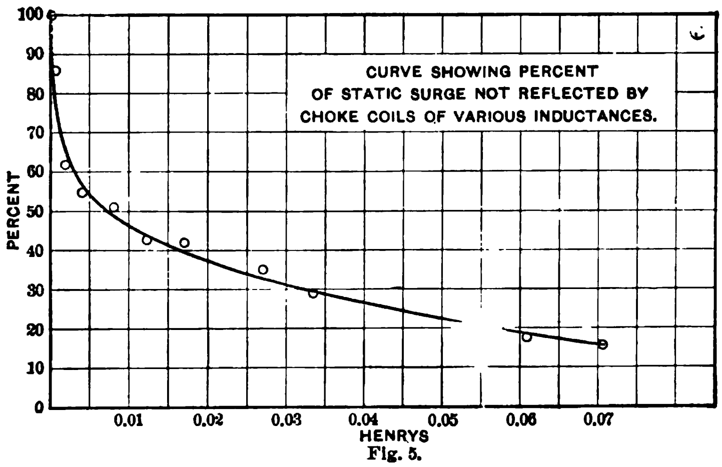

Fig. 5.

A reasonable deduction from Fig. 5 is that coils of very low inductance are practically useless; while for coils of inductance greater than 0.06 henry the protection increases very little with the increase of inductance in the coil.

Moreover, with increase of inductance in the choke-coil we encounter another difficulty. These inductances, of course, produce a drop in voltage. The electromotive force across the terminals of a coil is proportional to the current in that coil, but approximately 90 degrees out of phase with the current. Hence when the power-factor of the load is nearly unity the resulting drop in voltage is relatively very small. If the power-factor of the circuit is low, however, the electromotive force across the choke-coil comes more into phase with the impressed voltage and becomes of consequence. Figs. 6 and 7 show curves based on inductances giving 1% drop per coil at 80% power-factor at 25 cycles and 60 cycles respectively. Thus in a one-phase circuit with coils on each side of the circuit, the drop at full load and 80% power-factor would be 2%. This value is simply assumed as an extreme maximum to which one might go. With power-factor near unity, even these inductances would not cause an appreciable drop.*

From Fig. 5 it would seem that from 0.002 to 0.025 henry should be the useful range of values from the point of view of protection. Figs. 6 and 7 indicate to what degree such inductances may be used.

From these it appears impossible to obtain much choke-coil protection for 60-cycle circuits of low voltage and power-factor and large currents on account of the prohibitive drop. In all other cases shown a suitable inductance may be inserted with a permissible drop. For higher voltages, the per cent. drop will be negligible. Also if the power-factor of the load is near unity, even such inductances as have been indicated as desirable will not cause an appreciable drop. In most circuits, a well-insulated coil of considerable inductance is of undoubted service.

From consideration of Fig. 4 it would apparently be possible to insulate a transformer so as to protect it against the probable surges but it would make a difficult and expensive design at best and under commercial conditions when various loops are required and perhaps also series and parallel operation of coils for full and half voltage such insulation would be impracticable.

The kind of electrical disturbances which has been assumed above is, of course, one of many of widely varying characteristics,

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*A rough rule for determining the inductance of a choke-coil without iron is to multiply the square of the number of turns by the length of the mean turn in inches and divide the product by 10^8. This gives approximately the inductance in henrys.

Example: A certain oil-insulated choke-coil had 186 turns and the length of the mean turn was 66 inches.

$$186^2 \times 66 \times 10^{-8} = 0.0228 \text{ henry.}$$

but it is the writer's opinion that it represents the typical destructive high-power surges which often manifest themselves.

THE LIGHTNING-ARRESTER.

Returning to the mechanical analogy and Fig. 1, it may be noted that the lightning-arrester is of the nature of a relief valve, which when a rise of pressure occurs at the point at which it is placed should permit the escape of a sufficient amount of the elastic fluid to limit the rise of pressure.

Considering the condition previously suggested, of a surge of the elastic fluid towards the piston representing the transformer, it is possible, if the size of the pipe and the velocity of the moving fluid is known, to determine how large a vent will be required to relieve the surge of the fluid as fast as it arrives without permitting any reflection. Now supposing similiar conditions to exist in an electric circuit, can any tangible result be deduced? It has been shown that electric impulses or waves travel along aerial conductors with a velocity approximately equal to that of light or electromagnetic waves in the ether.* Also the charge or amount of electricity per unit length of conductor is proportional to the electrostatic capacity of the conductor, and the potential to which it has been raised, in the same way that the amount of fluid in the illustrative pipe is proportional to the volume per unit length and the pressure.

Now considering, in the case of the pipe, that the initial condition of the elastic fluid before being disturbed was that of very low inherent pressure, the wave resulting from the redistribution of sudden local high pressure will produce a mass velocity or velocity of the particles of the fluid itself very nearly equal to that of its velocity as a wave. On the other hand, if the normal pressure is such that the disturbance represents only a small

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*The rate of travel of electric waves along a wire is not a fixed value, but depends on the distributed capacity, the resistance, and inductance of the line. This rate of propagation is given by the expression,

$$\sqrt{\frac{2\omega}{C\left\{\sqrt{R^2+L^2\,\omega^2}+L\,\omega\right\}}}$$

(Bedell and Crehore)
Page No. 199.

which gives the rate of propagation in miles per second, if C, R, and L are given in farads, ohms, and henrys per mile. It may be found from this expression that for all sizes of copper down to No. 6, which is about 2 ohms per mile, and for all frequencies down to 150 cycles per second, the rate of propagation is not reduced more than 10 per cent. from the maximum.

per cent. change, the mass velocity of the fluid composing the wave at a given instant will be small compared with that of the wave itself. The latter condition is that existing in the case of ordinary sound waves. If, however, a tremendous explosion occurs, the wave of air is accompanied by a large mass motion. The action in the former case, or that of low inherent pressure, is also similar to that which will occur in a pipe when a valve is suddenly opened and closed, permitting the escape of an elastic fluid from a reservoir into the empty pipe. If this fluid is heavy and encounters little resistance, it will impinge on the closed end of the pipe and rebound. The action in an electric conductor under a severe disturbance, is more truly represented by considering the normal pressur very low compared with that produced by the disturbance. This would at least be true if the sudden rise should occur at or near the zero of the electromotive-force wave.

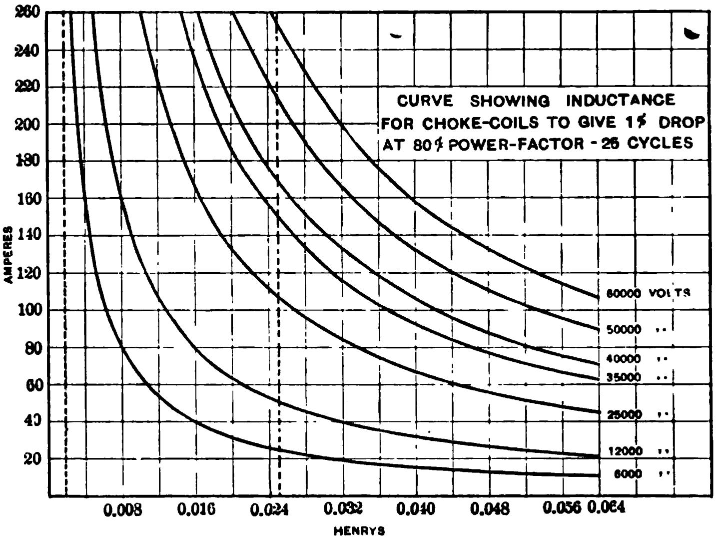

Fig. 6

The above illustrations are simply to show the reasoning which leads to the following deduction. Assume that a potential wave of irregular contour is approaching a transformer protected by a vent or lightning-arrester. Assume some part of this wave to have a value of 100,000 volts. If the electrostatic capacity of the conductor to ground is taken as 0.0135 microfarad per mile, which is approximately correct for the ordinary transmission line, there will be a charge of 0.00135 coulombs per mile. If this charge is arriving at the rate of 186,000 miles per second there are 251 coulombs per second or 251 amperes to be disposed of. Dividing 100,000 by 250 gives 400, which if true resistance would just let this surge escape without reflection if used as a series resistance to the vent or arrester. If the potential of the incoming surge is higher or lower the charge per mile becomes correspondingly higher or lower, and this critical value of resistance

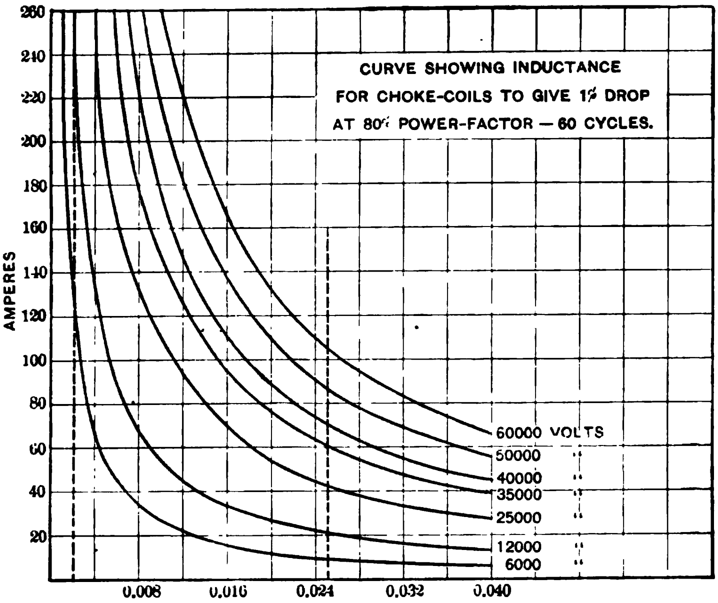

Fig. 7.

would remain the same. If there were some kind of recording meter capable of operating under such conditions, placed where the vent is connected, it would leave a record of the potential of the arriving charge, or to some degree the contour of the wave or surge. If a resistance greater than the critical value is used there will be a partial rise and reflection and a partial escape; but if the resistance is of less value the surge of potential striking the transformer windings will be similar to the contour of the incoming wave but of lower value. If, in the extreme case,

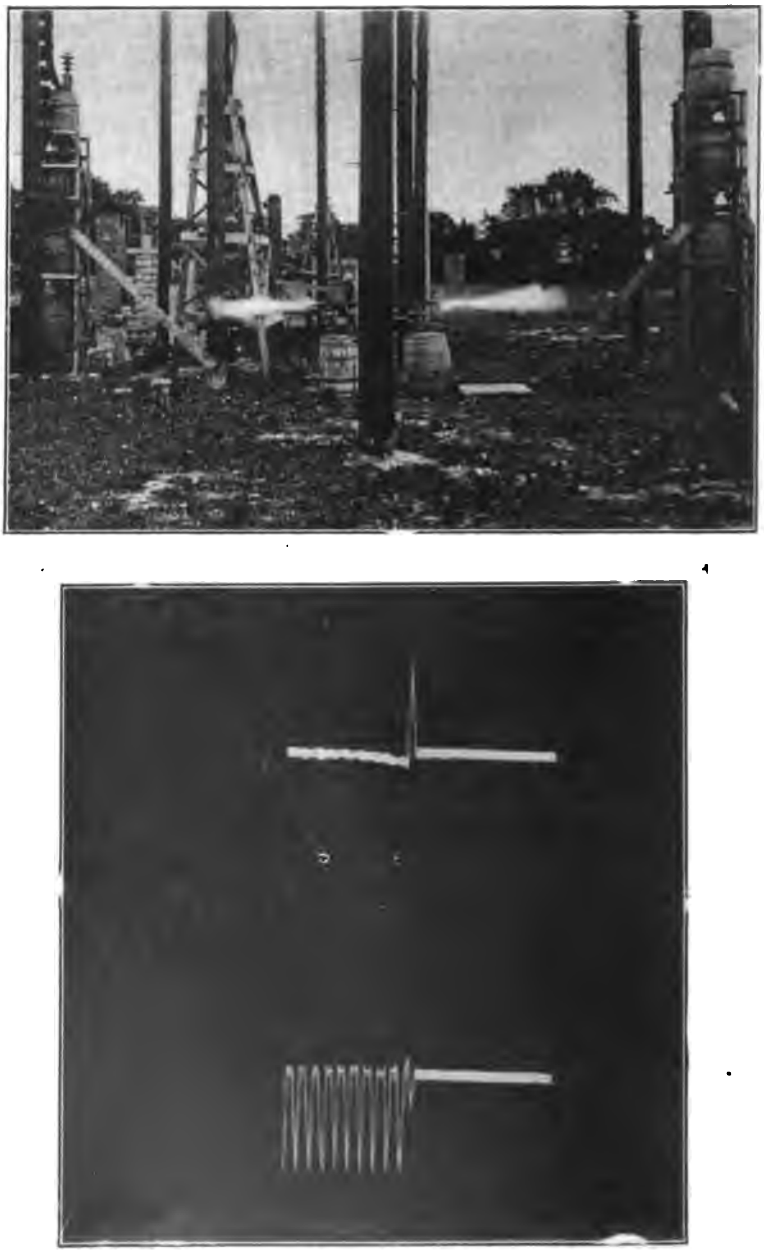

FIG. 8.—Operation of expulsion fuse. Voltage, 38,000 to ground. Capacity on circuit, 7500 kw. Length of line, 23 miles. Fuse wire of No. 30 copper. Upper curve of oscillogram shows current; lower curve the electromotive force.

there is no resistance, the charge will escape as rapidly as it arrives. In the case of the pipe and elastic fluid of the analogy, if the vent is too large the inertia of the moving fluid might produce a partial vacuum with a resulting return flow or oscillation. This may, of course, also occur with the electric discharge but it is possible that the inevitable resistance of the ground connection will limit any such effect.

From the above considerations it appears that the series resistance of an arrester should be very low and not greater than 400 ohms in any case, if the arrester is properly to serve its purpose. The reasoning and calculation given is perhaps a rough way of reaching the result, but it is on the whole not far from the truth, and it is in accord with the writer's experience. No exact formula can, of course, be applied absolutely to such irregular phenomena, but if the general assumptions are correct the result forms a guide sufficient to enable us to recognize and dispense with useless devices.

Having disposed of the series resistance from one consideration it is found, however, that no arrester with a reasonable gap will disrupt its dynamic arc if the circuit is carrying power from generators of large capacity unless the power current is limited in some way.

By the use of multigaps of non-arcing metal of such number that a rise of 300 % will just break over, and then by adding an equal number of gaps shunted by resistance, an arrester may be made which on moderate power will disrupt its arc without the use of series resistance; but if the gaps are limited to such a number as to break over with a potential of from 150 to 200% of normal and there is no limiting resistance, the arrester will almost invariably burn up before many discharges have passed over it.

A COMPARISON OF ARC-SUPPRESSING DEVICES.

The two devices most generally used for disrupting the arc in an arrester are the horn-type gap and the non-arcing metal multigap. On circuits where the power is so limited that the short-circuit current is not more than 50 amperes, either device should work without series resistance. Where the power is very large, however, as on the usual transmission line, the non-arcing metal is superior to the horn-type, in that the arc is easily suppressed with a much lower resistance, and suppressed more quickly.

It was found on a voltage of 38,000 to ground from a three-resistances usually come in this class, while carbon, carborundum, and graphite have an entirely different characteristic in that the equivalent of a stick or bar seems to be a function of its length, and several bars in parallel will give an equivalent gap practically the same as single bar. It has been suggested that such granular material acts under static discharge as a mass of conducting particles partly in contact, and the effect is that of a series of minute gaps in the resistance.

THE GAP AND FUSE ARRESTER.

Considering the effect of a resistance on a discharge path according to the mechanical analogy, it appears desirable at times to provide something in the nature of an absolute relief vent. A gap and a fuse of fine wire serve this function best, but the fuse should be of either the enclosed form or the expulsion type. An open wire fuse will almost invariably take so long to suppress its arc that it is likely to open the circuit-breakers, while the same wire enclosed in a tube will open its arc in one or two alternations. There are shown herewith photographs and oscillograms of fuses blown on a generator capacity of 7500 kw., three-phase, and at 38,000 volts from one leg to ground. It may be seen that the No. 30 copper wire opened at the end of one alternation, while a No. 22 copper wire lasted two full waves. The fuses were blown at the end of 23 miles of line but no serious rises of potential are shown. With the larger fuse, the first voltage wave after the fuse opened shows a rise of about 20%. The circuit-breakers were not tripped at any time.

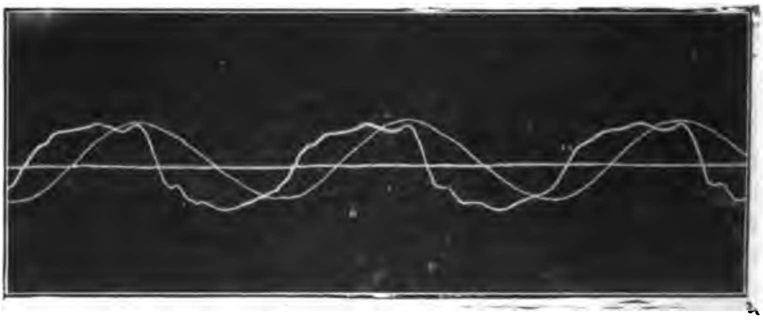

FIG. 10.—Current and voltage on 12,500-volt unit of electrolytic lightning-arrester. Volts. 9000; amperes, 0.2.

Experience shows that several gaps and fuses may be placed in parallel, and usually only one fuse will blow at a time. From the fact that so little secondary disturbance is caused on the line, such fuses appear to be an excellent expedient to use where the lightning disturbances are liable to be too severe to be relieved by a self-restoring arrester.

THE ELECTROLYTIC ARRESTER.

As may be seen, what is really needed is a device having the characteristics of a safety valve, that is, something that will hold the operating pressure at all times, but furnish such a free vent that no pressure much above the normal can be maintained, no matter how suddenly such abnormal pressure may occur. Such a device has been found in the aluminum electrolytic cell.

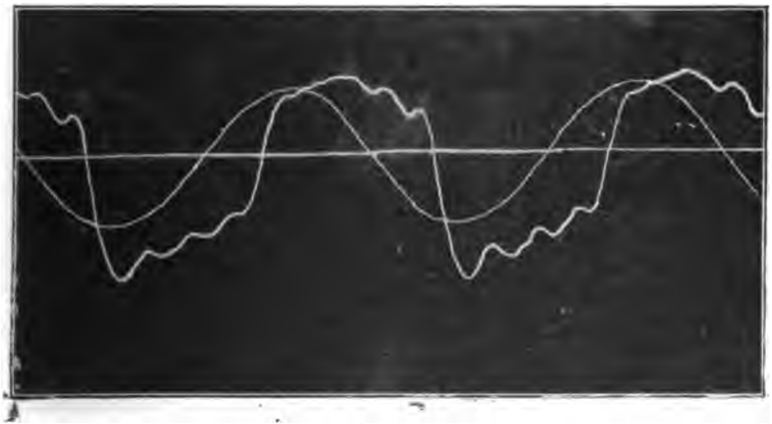

FIG. 11.—Current and voltage on 12,500-volt unit of electrolytic lightning-arrester. Volts, 12,250; amperes, 0.41.

In certain electrolytes, aluminum forms a non-conducting film on its surface. This film is very thin, comparable in dimensions to a wave length of light—but in a suitable electrolyte will withstand a voltage of 380 to 400. Above this voltage, the film will be punctured with myriads of small holes letting a large current through, but resealing again as soon as the pressure is reduced. The equivalent spark gap of such a cell is a function of its dimensions, and it is a simple matter to make a unit for 10,000 volts which will have an equivalent gap representing 12,500 volts. If a gap which will also break at 12,500 volts be placed in series with the cell unit, the equivalent gap of the combination will still be approximately 12,500 volts. In other words, the severest discharge from a condenser representing several miles of line and charged to 50,000 volts, will pass through the device without a potential of more than 12,500 volts existing over its terminal.

FIG. 12.—Total arc on horn gap with 25,000 volts, 25 cycles.

Apparently this cell can be connected in series with a suitable gap between each line and ground, and will suppress all abnormal rises of potential at that point. As to the kind of gap, a non-arcing multigap has been found very satisfactory while a small horn gap seems to work nearly as well. The power current taken being less than one ampere, the arc rises a few inches on the horn and goes out quietly. At this time no statement can be made as to which form will prove the more desirable.

Fig. 12 shows the total arc formed on a 25,000-volt, 25-cycle circuit. That is, the exposure has continued from the time the arc first started at the bottom of the gap until it broke at the top. The total height of the arc travel is about 10 in., and the arc broke when about 5 in. long. This arrangement has been used up to 40,000 volts.

The oscillograms shown in Figs. 10 and 11 represent the voltage and current characteristics of a 12,500-volt unit. The applied voltages are 9000 and 12,250 respectively, and the currents are all less than one ampere. The smooth curve shows, of course, the voltage, and the irregular one the current which is about 70° in advance of the electromotive force and is largely condenser current. In the test shown in Fig. 10 the applied pressure was about 9000 volts effective which was such a value that the maximum of the electromotive-force wave was just below the breaking through point of the cell. The small humps on the upper halves of the current waves show that, in fact, there was a slight breaking through at the point of maximum electromotive force. Fig. 11 shows how this breaking down or puncturing of the film has been increased by a moderate increase of voltage—the effective applied voltage in Fig. 11 is 12,250. The current taken by the device may be divided into two parts and called for convenience "condenser" and "leakage" currents.

They both exist at all times when an alternating electromotive force is applied, and one is wattless while the other represents power. As the voltage is increased, both condenser and leakage current are increased, but during the period while the electromotive force is highest, there begins to be increasingly large leakage current. The unsymmetrical shape of current wave which appears in Figs. 10 and 11 is due to the fact that the aluminum plates are in tray form and the exposed plate area in one direction is less than that in the other and the solution in contact with the lesser area is more dilute than the other. As the voltage is still further increased, a very acute peak develops near the maximum point on the electromotive-force wave. A surge or electromotive force peak from any other source is allowed to pass and relieve the line, exactly as in the case of a safety valve, while the power current, which can follow is insignificant.

In general it can be said that the electrical characteristics of this device are ideal for the purpose, but there were many mechanical difficulties met with in making it in a form suitable for commercial use. Nearly all the difficulties have been overcome, but an endeavor is being made to test out all possible points in service.

It is to be hoped that the long looked for protection against all potential rises has been found. It is needless to say that no effort will be spared to make it fulfil its promises.

DISCUSSION ON "RECENT INVESTIGATION OF LIGHTNING PROTECTIVE APPARATUS" AT NEW YORK, DECEMBER 28, 1906.

Ralph D. Mershon: There is probably no other natural force amongst those with which modern engineering has to deal of which so little is intimately known as of lightning. In most engineering problems it is possible to control and reproduce at will the conditions actually existing in practice, and thus study the phenomena resulting therefrom; or, if this is not possible, there is a natural repetition of the phenomena of sufficient regularity so that they can be studied and traced back to the elements on which they depend. With lightning this is not so. The conditions existing in practice cannot be controlled, and the elements involved are so enormous, numerous, and variable that it is impossible to reproduce them. The natural repetition of phenomena is at such irregular intervals, and the phenomena, when they do occur, are apparently so erratic, due to the number and variability of the elements on which they depend, that no satisfactory searching study has been made of them.

As a result, we have no intimate knowledge of lightning and the conditions governing it and its effects. Theorizing in regard to it is, in the lack of definite experimental data, of little value. Theory cannot be much more than guessing, and, within certain limits of probability, one guess is just about as good as another. There is about as much use in trying to forecast the weather for a certain day next year as to tell what lightning will do.

In view of the above, I am always more or less skeptical of any theories advanced in regard to lightning or lightning protection; at any rate, unless actual practice has shown that there may be some foundation for the theory. Even though practice should uphold the theory, as it has in a few instances, I should be skeptical, for, as has been the case more than once, the next installation may upset both practice and theory.

We are, I think, at times too much inclined to theorize without a sufficiency of data; to attempt to reason from a few facts pieced out with such fundamental data as we have at hand, instead of first experimentally obtaining at least a fair amount, if not all, the information possible, directly applicable to the subject in hand, and then endeavoring to formulate a theory. The paper under consideration this evening is, it seems to me, somewhat open to criticism in this regard.

By means of the data of Figs. 4 and 5 obtained on one transformer, having a certain internal electrostatic capacity and subjected to a frequency or steepness of wave-front, which may or may not approximate that in the case of lightning, the endeavor is made to specify, within certain limits, the inductance which will form an effective protection. I think that if it were worth while, it could be shown that with other transformers and other frequencies of discharge, the criteria by means of which the writer of the paper has fixed the limits of effective inductance would be very materially modified. In my opinion the author would have done much better to have turned to his Figs. 6 and 7 and said: " Here are curves showing what in practice we can stand in the way of reactance. Guided by them, let us use all the reactance permissible." Even then, I should not be inclined to agree with him as to the advisability of choke-coils. A choke-coil of any considerable size is an awkward and an expensive thing. It is expensive not only in itself, but in the space it takes up, and, besides, it usually adds complication to the station wiring, the high-voltage wiring which it is especially desirable to keep simple.

If we must have choke-coils, let us put them in the same case as the transformers, and so save the complication in station wiring. Better still, let us do away with them altogether, and put such amount of insulation as may be necessary on the end-turns of the transformers, such amount of insulation as will take care of a considerable strain between the end-turns. Then, if we use a low-resistance arrester or its equivalent, we shall, I think, have ample protection.

As between a high inductance choke-coil in connection with a high-resistance arrester, and no choke-coil in connection with a low-resistance arrester, I much prefer the latter. And it is possible to have the low-resistance arrester equipment, as I will show later on, even though the electrolytic arrester described by the author should not prove to be all that it promises, but which I hope it will realize.

I have known of many cases where choke-coils of considerable reactance in connection with arresters of considerable resistance have failed to protect under severe conditions, but I have never known a case where very low-resistance arresters or fused arrester-gaps have failed to protect. I have known of a number of cases where apparatus has been damaged not only in spite of the choke-coils installed with it, but apparently because of them, due to disturbances on the circuit other than lightning, and a piling up of potential of the transformer terminals,probably because the choke-coil kept the transformer from freely ridding itself of a charge set free in its windings. Such happenings as this would seem to indicate that if a choke-coil were used, an arrester should be installed on each side of it.

Transformers will undoubtedly be more expensive with heavily insulated end-turns, but I think that in most cases the extra expense will be little, if any, greater than that of the separate choke-coils and the space they take up. This will certainly be the case for such extra insulation as will be necessary with a low-resistance arrester. The demand for a number of voltage taps need not interfere with the end-turn insulation, if the desired variation in the length of the transformer winding be obtained at the middle of the winding; that is, at the junction of the two halves of the winding instead of at the ends. Multiple series connections of high-voltage windings ought not to be often required, and I believe that as time goes on they will be required less and less; but even where they are required, I believe that the same heavily insulated end-coils might be used as end-coils for both series and multiple connection, and meet most of the requirements in practice.

I am inclined to doubt the correctness of the opinion that the author seems to hold relatively to the resistance of lightning-arresters. I have reason to believe that under some conditions even a high-resistance arrester will be of benefit; and I do not think the author himself is prepared to state that the high-resistance arresters now installed afford no measure of protection. I do, however, agree that a low-resistance arrester is desirable at all times, and absolutely necessary for proper protection under some conditions.

It is possible to have a system of lightning protection which will automatically adjust the resistance of the path to ground to that value necessary to take care of the discharge. Suppose we assume that the magical 400 ohms worked out by the author is the resistance which must not be exceeded under extreme conditions. Suppose that with a given voltage and generating capacity, a horn, or other suitable arrester, will operate satisfactorily, if it has, say, 2000 ohms in series with it. Suppose we have five such arresters connected to each line wire, each arrester having 2000 ohms in series with it. Set one of the arresters on each wire for low-striking electromotive force; another arrester on each wire for a higher striking electromotive force; another for a higher, and so on to the fifth arrester, set for the highest striking electromotive force which the apparatus to be protected can, for a short period of time, safely withstand. Now suppose there is a rise of voltage on the line under such conditions that one 2000-ohm path to earth will properly discharge it. The lowest gap will flash over, and discharge take place through the 2000 ohms in series with it, this discharge keeping the electromotive force of the disturbance down below that necessary to strike across the next higher gap. If a disturbance occurs requiring a 1000-ohm path, the lowest gap will strike, also the next lowest, giving two 2000-ohm paths in multiple for the discharge. Similarly, with other disturbances more severe, more and more of the gaps will flash over until, in the extreme case, all five gaps will be active and the resistance of the combined path to earth will be 400 ohms—that specified by the author. If desirable, there might be one or more gaps having fuses in series with them, so that when they acted, the discharge would have a path to earth of practically zero resistance.

The above scheme of lightning protection might be carried out to any extent, and any desired number of gaps be used, the result being that under any given condition the path to earth would have a resistance as low as necessary to take care of the disturbance upon the line and that the disturbance to the transmission system, due to the dynamic current which would follow the lightning discharge, would be proportionate to the necessities of the case. In an extreme case the disturbance to the system due to the dynamic current over all the gaps might be such as to cause a shutdown, but the apparatus would be protected. A shutdown without any damage to the apparatus is preferable to a shutdown resulting in apparatus which has to be patched up; fortunately, such extreme disturbances are rare.

Such a system of protection as that described would apply not only to disturbances requiring a path to earth, but also to discharges passing from a conductor to conductor. It is to be noted that in such a system the operation of successive gaps not only reduces the resistance, but also the inductance of the path.

I have for some time past made use of the scheme of lightning protection outlined above, except that only three sets of gaps are used on each line wire, and the highest gap has a fuse in series with it. My experience so far, extending over one lightning season, has been very satisfactory. A previous experience, extending over several seasons and with a system of protection similar to, but much less elaborate than that with the three gaps just described, was also satisfactory. I have come to believe that such a system is about as near to being an absolute protection for station apparatus as could be expected. This assumes, however, that the apparatus has that margin in insulation strength which good apparatus should have, enabling it for a short period of time to withstand considerably more than its normal voltage.

The electrolytic arrester described by the author is a very interesting and promising piece of apparatus. I have seen it in experimental operation, and, so far as experiments go, it seems as if it might be effective. It remains, however, to be seen how it will behave in practice; what difficulties may arise due to the evaporation or freezing of the electrolyte, or to the sudden formation of vapor, in the case of a lightning discharge of extreme severity. Any or all of these troubles may be met with, but no doubt they can be overcome, the latter possibly by using a number of these arresters in multiple, either in series with gaps of the same size or set for different striking electromotive forces. It looks as if we may at last have the ideal lightning-arrester and I sincerely hope that this is the case.

In my opinion a very desirable requirement of a lightning-arrester is that it should be capable of being installed outdoors. I believe that as time goes on more and more high-voltage apparatus will be installed outdoors, instead of in a building. I think the time will come when not only lightning-arresters, but bus-bars, transformers, and even automatic circuit-breakers, where such are used, will regularly be installed outdoors. It seems rather illogical, and, from some standpoints, almost ridiculous, to instal high-tension bus-bars in a building with barriers and all sorts of other complications, when the lines led off the bus-bars go immediately out of doors, unprotected, and often installed upon very questionable line structures.

I understood Mr. Jackson to say that in obtaining Fig. 4, the middle point of the transformer was grounded, so that the discharge went through half of the transformer winding only. I would like to ask if he took any observations similar to those of Fig. 4 on the other half of the transformer winding? It would be interesting to know what voltages could be obtained on the other half of the winding? It would have considerable bearing on his statement indicating that the iron renders ineffective the space occupied by it, so far as the inductance of the coil is concerned.

Chas. P. Steinmetz: This paper deals again with those four elements which, since the earliest days of electrical engineering have constituted the parts of lightning protective apparatus; namely, the resistance, the inductance, the spark-gap, and the circuit-opening devices.

In regard to the reactance or choke-coil, I also fully believe in the effectiveness of the reactive-coil. It is obvious that the reactive-coil cannot be considered as a protection against all of the manifold manifestations of atmospheric electricity or internal surges; anybody can see that against a slow accumulation of electrostatic charge on the system by induction from the clouds, etc., whereby the total system rises as a whole in potential above ground, a reactive-coil cannot protect; also, it cannot protect appreciably against a very low-frequency surge where the oscillation is of enormous magnitude and of a frequency not much above the normal line frequency. Then any amount of reactance which it is permissible to put in circuit, will not offer a sufficient protection. Hence, the reactive-coil is not a universal protective. However, it can be shown experimentally that at least against high-frequency oscillations, against travelling waves of steep wave-front, the reactive-coil offers a very marked and satisfactory protection.

I cannot agree, however, with the paper regarding the numerical values of the minimum effective reactance. I believe the numerical values given are not correct general conclusions, but merely incidental to the particular conditions of the experiment from which they were derived. The spark-gap was connected across the 200 end-turns of the transformer, and it was found that the electrostatic stress across these 200 turns of the transformer, without reactive-coil, or with very small reactive-coil, had an equivalent spark-gap of one inch; that is, about 20,000 volts. The spark-gap was reduced to one-half by an inductance of about 7 millihenrys. If the writer of the paper had connected the spark-gap, not across 200, but across 20 end-turns only, he would have obtained a curve similar to that given in Fig. 5, but with an entirely different set of abscissas, and would have found as minimum effective inductance sufficient to reduce the spark-gap to one half, about one-tenth of the value given in the paper. If he had connected the spark-gap across the two end-turns, probably the minimum effective reactance would not have been 7 millihenrys, but something like 0.07, or about one hundredth part of the value recommended, so that the effective reactance depends on the number of turns across which the electrostatic stress is observed. The error made by the writer is one of those into which I believe all of us who have done experimental investigating and drawn conclusions from it have fallen at one time or another; that is, to draw general conclusions, especially regarding the magnitude of a phenomenon, and then afterward find that these conclusions are not general, but special results of the particular conditions under which we experimented.

Let us see what happens if a voltage is suddenly impressed upon a transformer, as here the voltage of the Leyden jar or the condenser, of about 50,000 volts, or by an atmospheric oscillation or travelling wave, etc., or the line voltage when connecting a transformer into the circuit. Before closing the circuit the transformer windings are at zero potential; in the moment of closing the circuit 25,000 volts are put on one terminal; that is, on the beginning of the end-turn, but the ends of this turn and the second turn are still at zero potential; and so at this instant the full potential of 25,000 volts exists across a single end-turn. An instant—a fifty-millionth of a second or so later—the current has passed along the first end-turn, and voltage exists at the beginning of the second turn, while the third turn is still at zero potential. In this instant the full potential of 25,000 volts is across two end-turns; that is, each gets about half of the voltage. Again, in another fifty-millionth of a second, the potential distributes across three turns, then across four turns, five turns, etc. You see the maximum potential difference which can exist without any reactive-coil across the first turn is the full voltage of 25,000 volts. The maximum potential difference across the second turn is half, half being across one turn and half across the other; across the tenth turn it is one-tenth, and across the 200th turn it is $\frac{1}{200}$ of the full voltage.

Suppose we take out the first nine turns and put them outside the transformer as a reactive-coil. The first transformer turn, then, is what was before the tenth turn; and at the same discharge, the same impressed voltage, the maximum potential at the first transformer turn is the maximum potential which was formerly got at the tenth turn; that is, it is one-tenth of the impressed voltage. That is, by putting nine transformer turns outside of the transformer and in series therewith, as a reactive-coil equal to only nine transformer turns, very much less than the minimum referred to by the speaker, the maximum electrostatic stress which can exist anywhere in the transformer is reduced to one-tenth of the previous value. But the maximum electrostatic stress across the 200th turn is reduced only from $\frac{1}{200}$ down to

$\frac{1}{209}$ of the full voltage, because it is now the 209th turn, and the sum of all the electrostatic stresses across the first 200 turns is not appreciably reduced at all. Hence if we use a reactive-coil equivalent to nine transformer turns, and measure the electrostatic stress across the first 200 turns, we find no appreciable effect, while actually we have reduced the maximum electrostatic stress on the most exposed part of the winding, the first transformer turn, to one-tenth of the previous value; that is, we have secured a very high protection.

After all, if a transformer breaks down internally by a sudden discharge, it is not the 200th turn which breaks down, or the 100th turn; it is one of the very first turns, where the electrostatic stress is the maximum, and where, therefore, there is a maximum potential difference many times greater than given by the data in the paper, which data give, not the maximum stress anywhere in the transformer, but the value integrated over a very large part of the transformer; that is, an average which bears no direct relation to the maximum, against which we have to guard.

I do not need to go into this matter further because this phenomenon of distribution of potential in the transformer windings at a sudden application of voltage has been very fully discussed, in the classical paper read before the American Institute of Electrical Engineers four years ago by Mr. Percy H. Thomas.* There this phenomenon is very fully explained.

I think it fortunate that such high reactance is not necessary, but that a very great reduction of the maximum electrostatic stress results from very moderate reactance; that is, by a reactive-coil which does not occupy as much space as the whole transformer. Obviously, the more reactance is put in the circuit, the more the stress on the transformer is reduced, but very soon it becomes a question whether it is more economical to build a larger reactive-coil, or to increase the insulation of the transformer end-turns. To insulate between the end-turns against full voltage is difficult, and an additional reactance is therefore desirable; but as we have seen, a reactive-coil of very few turns only, already reduces the maximum stress at the end-turns to a very few per cent. of the maximum possible stress, and so to a value against which sufficient insulation of the end-turns can easily be provided for, without appreciable increase of size and cost of the transformer. A moderate size reactive coil and additional insulation of the transformer end-turns is preferable, because it does not make it necessary to have such a very large reactance, which spoils the regulation of the system by two per cent. or becomes impracticable altogether on a large-current low-voltage system.

This feature is also important in considering the question whether the reactive-coil is a reactive-coil at all. It might also be stated as a conundrum for high-frequency phenomena:

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* TRANSACTIONS of A.I.E.E., 1902, Vol. XIX, p. 213.

when is a reactive-coil not a reactive-coil? In speaking of reactive-coils as guarding against high-frequency oscillation: we always assume that such a coil contains inductance and a very small resistance; but we usually forget that it also contains distributed capacity, that there is a capacity from turn to turn which may be relatively small where circular conductors are used. There is, too, a considerable distance between turns; this

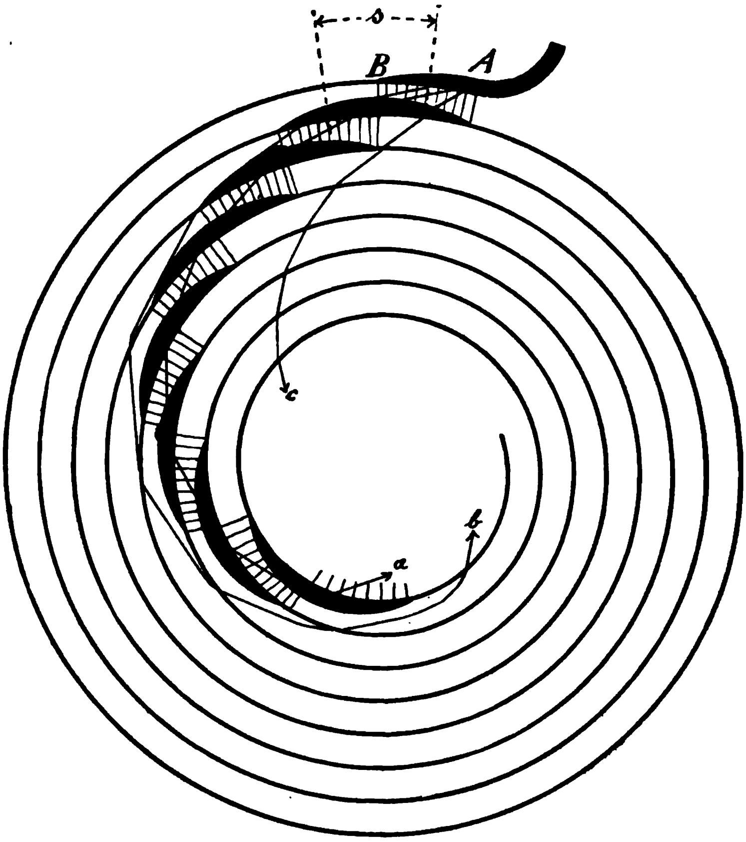

Fig. 1.

becomes very much larger where flat conductors wound in a flat coil are used, very much larger where we submerge the reactive-coil in oil, due to the higher specific inductive capacity of the oil, the specific capacity of the oil being two or more times that of air, and due to the shorter distance between the turns, permitted by the higher disruptive strength of the oil. At such very high frequencies as are produced by spitting from the line, by brush and spark discharges, by an arcing ground on one side of an isolated three-phase system, and many other such phenomena, the electrostatic capacity of the reactive-coil begins to be appreciable.

What happens I can sketch only roughly. Let the reactive-coil be shown diagramatically in Fig. 1, as a spiral, with the turns inside of each other. If a discharge enters at the lead A, if the frequency is high enough the current does not go around the complete spiral, but the current passes from one conductor to the next conductor through the capacity between the turns as a condenser. The current, starting at full value at A, gradually tapers down in the first turn, to nothing at B, within a limited distance; in the second spiral, the current is zero at A and gradually rises to a maximum at B. In the same way the current passes from the second to the third turn, etc. The current thus transfers across from turn to turn by the electrostatic capacity between the turns, gradually rising in each turn, by transfer from the preceding turn, and fading out again by transfer to the next turn. Thus the current flows a short distance only in each turn, but does not go around if the frequency is high enough.

Assume that:

L = inductance per unit length of conductor,
C = capacity per unit length of conductor,
N = frequency of the oscillating current, or frequency representing the steepness of the travelling wave.
s = length from condenser center to condenser center, then
$C\,s$ = capacity of each of these condensers formed by successive turns.
$L\,s$ = inductance of the short path of the current from condenser-center to condenser-center.

The current has an infinite number of paths, a, b, c, etc.

There is one path, on which the capacity reactance: $k = \frac{1}{4NCs}$ equals the inductive reactance: $x = 4NLs$ and the total impedance thus is a minimum, equal only to the ohmic resistance; that is, this path is non-inductive, and the current flows across the reactive-coil on this path.

In this case:

$$k = x$$

it follows:

$$s = \frac{1}{4N\sqrt{L\,C}}$$

or:

$$N = \frac{1}{4\,s\sqrt{L\,C}}$$

That is, if:

L is the inductance, C the capacity per unit length of the conductor, if the frequency of discharge is high enough, the current does not follow the turns of the reactive-coil, but passes in a spiral, non-inductive path across the coil, and the reactive-coil is not a reactive-coil. The frequency where s equals the length of one turn, gives the limiting frequency at which this phenomenon is completed, at which the last inductance has disappeared. This limiting frequency is very high, somewhere in the range between 10,000,000 and 100,000,000 cycles, but it is a frequency which does occur in discharges from a line, not a discharge which comes from a long distance, but a frequency which occurs where a steep wave approaches a station, and then meeting any obstruction spits over to other conductors near by, or into space. This phenomenon has to be considered when dealing with reactive-coils at very high frequency, and may be one of the causes why reactive-coils occasionally do not protect, but let extremely high frequency pass, just as well as low frequency, and act only in the case of intermediate frequencies.

The phenomena resulting from distributed capacity in the reactive-coil at extremely high frequency are obviously more complex than those illustrated above. For instance, during the decrease of current by transfer to the next turn, across the intervening capacity, a transfer back to the preceding turn takes place also, and so a second parallel path of current, of lesser intensity, appears ahead of the main path a, as shown by b in Fig. 2, a third path at b', etc., and in similar manner, back of the main path, secondary paths c, c', c'' etc., appear. These secondary paths, overlapping at the opposite side of the coil, result in various interference phenomena. Thus if all the turns of the coil are of the same effective length, at those frequencies at which the length of turn is a multiple of s, resonance effects intensify these standing waves; while at an intermediate frequency the standing waves passing around the coil in opposite direction, meet in opposition and thus neutralize. Again, with a coil in which the diameter of the turns tapers, resonance appears in some, opposition in other turns, and radially distributed nodes appear at all frequencies, shifting with a change of frequency

Coming to the next element of the lightning-arrester, the series resistance, I fully agree with the sentiment—which can be read between the lines of the paper—that the best series resistance is the one of lowest value, and the lowest value is zero. There are, however, two points of view; one point is that of the designer of the lightning-arrester, and the other that of the operator of the transmission system. For the protection and safety of the lightning-arrester, the higher the series resistance the better; and it is extremely difficult to produce a lightning-arrester without series resistance, which is really safe against self-destruction. But from the point of view of effective protection of the system, any series resistance is objectionable. Here also the writer of the paper has calculated numerical value for one particular condition, and concluded therefrom that 400 ohms series resistance is permissible. This conclusion is justified only for the particular condition where an electrostatic charge of 100,000 volts appears somewhere on the line and approaches the station along the line. There may be other disturbances in which this series resistance is not permissible. It may happen that in a station a short circuit takes place, and instantly ruptures. For instance, by some overload the circuit opens, but the switches fail, as should not happen, but still occasionally happens; that is, the switches burn up by a flaring arc and the short-circuiting arc ruptures itself spontaneously, explosively, as such arcs occasionally do at the maximum of the current wave. That means a rupture of the short-circuit current. That current cannot instantly cease in the system, but continues to flow, and not having a path merely backs up as voltage. It is obvious that in any large system the voltage produced by the instantaneous rupture of the maximum short-current circuit cannot be appreciably relieved by the discharge over a 400 ohms resis-

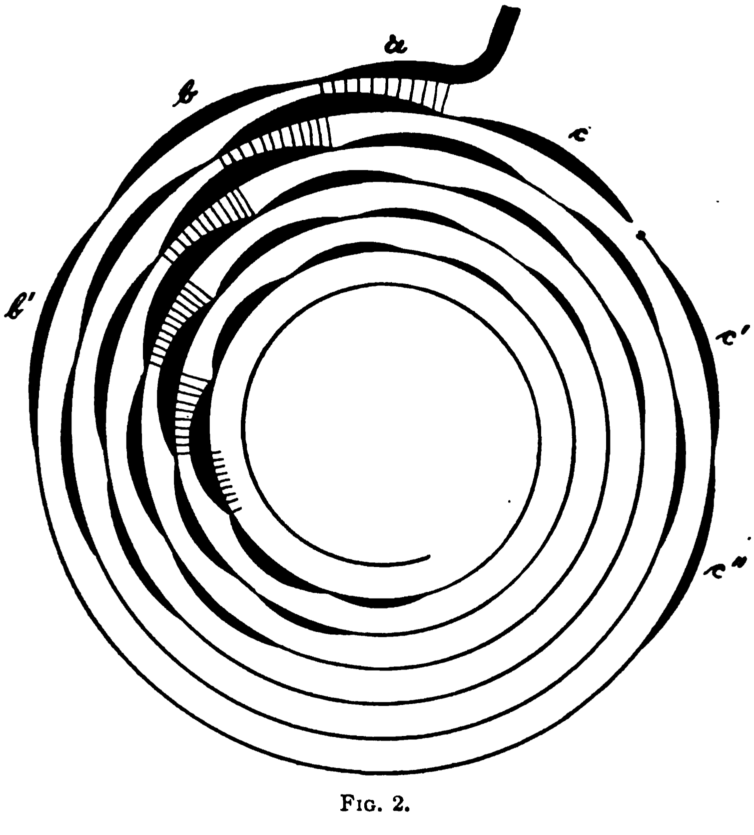

FIG. 2.

tance. A circuit with 400 ohms resistance will not reduce the destruction to any appreciable extent. For instance, at the Milwaukee convention last May, Mr. Osgood of the New Milford Power Company reported on the low-frequency surge in his system produced by some person who threw an umbrella handle into the transmission line at 33,000 volts. Or in cases like that of a metropolitan system, where a short-circuit oscillation or surge occurred with a current sufficiently large to bend heavy copper bars, and at a voltage jumping across seven inches of air. No protective device with 400 ohms series resistance would have any appreciable effect in relieving such a surge. In the case of 400 ohms series resistance, or any series resistance, there always comes a point where the magnitude of the surge is such that the series resistance becomes fatal.

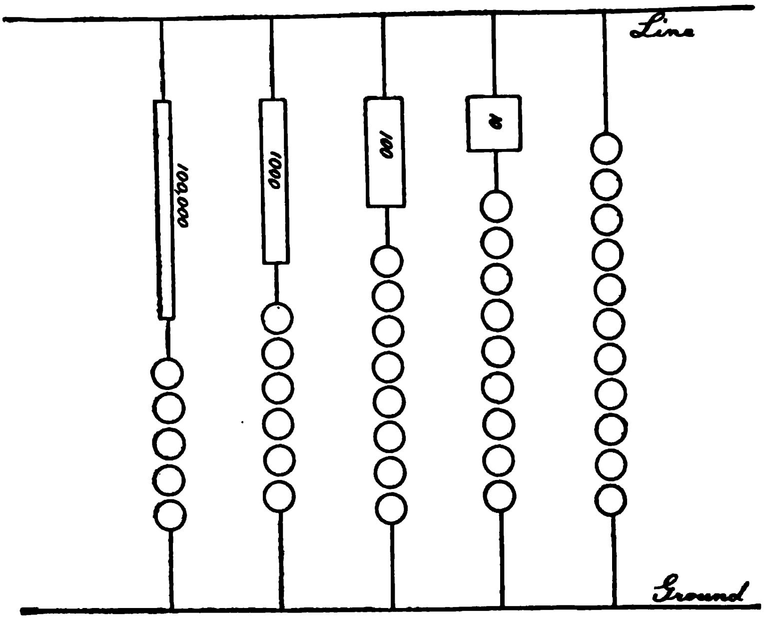

FIG. 3.

In regard to the electrolytic arrester, I may say that it is a very interesting apparatus. I know that Professor Creighton has been working on this type of lightning-arrester for several years, and I believe some such arresters have been out in commercial service on high-potential lines for a year or two. I expect we shall hear something of the performance of these arresters either to-night, or at the meeting of the Institute for which Professor Creighton promises a paper

In regard to Mr. Mershon s proposition, I approve of his type of lightning-arrester, a number of spark-gaps set for different voltages, with different series resistance, a low-voltage spark gap with a very high resistance, and then a little higher voltage spark-gap with somewhat lower resistance, etc., so giving the current the choice either to jump only the last spark-gap with high resistance limit, or the next one with lower resistance, or the next, etc. We know that a number of small gaps in series are more effective than one large gap in opening the circuit, so that several gaps in series are preferable. Suppose the first path contains 100,000 ohms, with a certain number of spark-gaps; the next arrester contains 1,000 ohms, with a few more gaps; the next one is 100 ohms, and still a few more gaps so as to require a higher voltage; then the next one is 10 ohms and still a few more gaps. If the designer of the lightning-arrester has sufficient confidence, the last path may contain still more gaps, and no resistance, as sketched in Fig. 3, diagramatically. There seems to me no reason why instead of separate spark-gaps for each path, the same spark-terminals could not be used for all, and the protective device built as sketched in Fig. 4. Even the same resistances may partly be used. Possibly we might go still further and connect on to

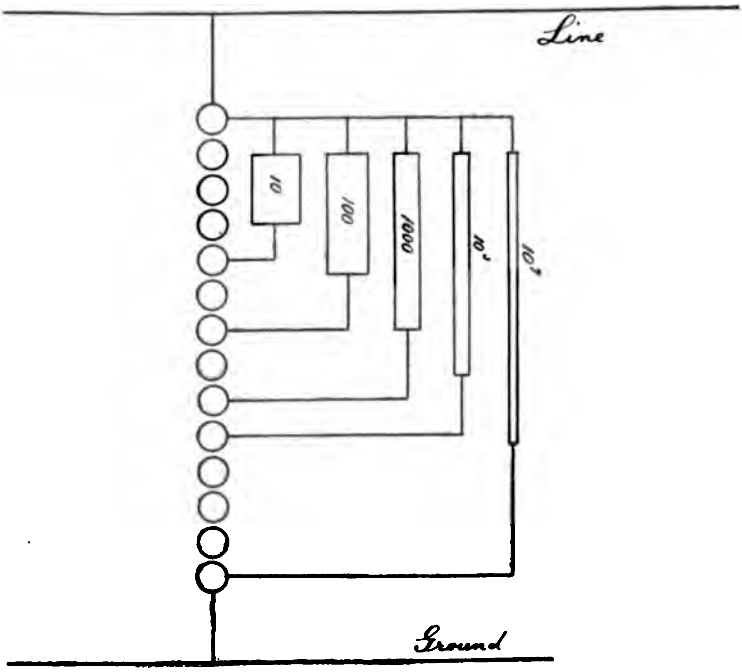

FIG. 4.

the next or to the ground line with a high resistance, so that a gradual accumulation of voltage can discharge steadily; this results in a very satisfactory arrangement for the discharge of lightning, because it would select the resistance according to the severity of the discharge and always use the least number of air-gaps and the highest resistance permissible by reason of the character of the discharge.

Percy H. Thomas: Somehow or other we do not seem to lose our interest in lightning-arresters, and I hope Mr. Mershon will not take away all of our discussion of theory, because if he does I do not know what we shall talk about.

I think a little more explanation of the method by which a series choke-coil protects the transformer winding is worth while. The point I want to bring out is that the concentration of potential on the outer turns results from the electrostatic capacity within the winding of the transformer. Suppose we have a transformer winding connected to earth on one side, and a static disturbance comes from the line; assuming that there is no capacity between the turns or to the ground in that winding, we will not get an uneven distribution of potential, severe at the line terminal and light at the other end, but a perfectly uniform distribution of potential throughout the winding, the same number of volts for each turn. Suppose we put a choke-coil between line and ground, and suppose the same disturbance to come from the line; as before we will get no concentration of potential, simply a distribution through the total winding of the transformer and the series coil; and each unit of induction will have the same voltage impressed upon it. Suppose, on the other hand, we have the actual case occuring in practice; that is, a winding with electrostatic capacity between each turn and ground and between adjacent turns (the latter having very much the same effect as the former); the capacity of each turn may then be considered as equivalent to a small condenser. Before the discharge from the line reaches the first of these condensers, the potential of the corresponding turn remains practically zero and there will be no change until the discharge from the line has flowed from the terminal to this first condenser, as Dr. Steinmetz has explained; and for a brief instant of time full potential is impressed between the terminal and this point. Then, as the charge penetrates, this potential is distributed on more and more turns. Suppose we assume *A* in Fig. 1 to be the line end of the transformer winding, and that the other end *B* is connected to ground. Then, in the first case where there is no capacity in the winding and no series coil, the maximum strains will be shown by Curve *I*, in which is plotted as ordinates the maximum potential which will be found on each turn. The resultant curve will be practically a straight line.

In the case in which we have capacity in the winding, however, and no series choke-coil, the curve of maximum potential between turns is shown by Curve II. Taking the case in which the winding has no capacity, and a series choke-coil is introduced at the point *C*, the distribution of potential will be as shown in Curve III, where each unit of inductance receives the same impressed voltage. In the case where the winding contains inductance and we have a series choke-coil, as usually met with in practice, we have a distribution of the potential as shown in Curve IV. The effect of the choke-coil is thus seen, in practice, to be the reducing of the maximum strain on the first turns only.

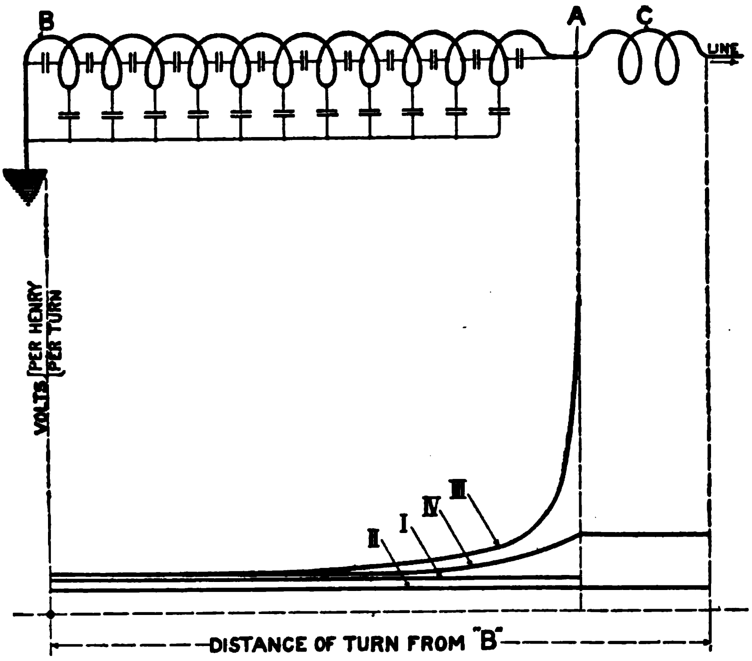

Fig. 1.

Of course the condition which determines how much potential will be impressed on the outer turns of the winding is the rate at which the charge penetrates the coil, and is controlled just as much by the capacity of the winding as by its inductance. The greater the inductance and the greater the capacity the slower will the discharge penetrate, and the greater will be the concentration of potential.

I think it will generally be admitted that one given value of inductance in a series choke-coil will not be suitable for protecting all sizes and types of transformers.

Mr. Jackson has brought out an interesting point: that a condenser which is stretched out over a long distance; that is, having distributed inductance and capacity, as a transmission line, charged to a given potential, cannot produce during discharge more than a certain current, and that using a definite resistance in series with such a discharge would always produce a potential proportional to the potential to which the line was previously charged. This condition, which is not true of a condenser where there is not a uniform distribution of capacity and inductance, is analogous to the discharge of water from a long trough or canal of uniform cross-section; in which case when once started the liquid contents would flow out at the mouth at a constant rate, neglecting resistance losses. However, it is hardly safe to apply this conclusion to a practical transmission line, since we may not have one, but several lines discharging through the arrester at once, and since we may have a direct lightning discharge passing to ground which will, of course, be controlled as regards its current strength by considerations other than line capacity.

I wish to call your attention again to another system of lightning protection, differing from the arrangement suggested by Mr. Mershon. Suppose we have a transmission line and have standard lightning-arrester apparatus of a type capable of caring for ordinary discharges continuously and without renewal. We may then add at some point, possibly between 1 and 5 miles from each station, a number of fuses in parallel, connected between line and ground in series with a spark-gap, each fuse having in addition a gap of its own. We then have an arrangement which will not only care for ordinary disturbances without attention or renewing of apparatus, through the arresters at the stations, but also for relieving severe discharges or passing direct strokes to earth through one of the fuses. and thus interrupting the generator current. The use of several fuses and series air-gaps insures that a number of severe discharges can occur without leaving the line unprotected. These fuses can also be easily arranged to be renewed while voltage remains on the line.

This system of protection is brought up at this meeting on account of the tests reported by Mr. Jackson, which indicate that a fine wire inclosed in a tube opens the circuit very quickly —in this case at the end of the first alternation—without rise of potential and without opening circuit-breakers, and presumably without disturbing synchronous apparatus. This result, if substantiated by later experience, as seems very probable, is of the greatest importance, as it eliminates one of the chief presumptive difficulties of fuse arresters: namely, the interruption of service from temporary short-circuit on the line. I suggest, however, the use of a German silver wire in place of the fine copper wire, as this will blow at a smaller current.

The electrolytic arrester is, of course, the item of greatest interest in Mr. Jackson's paper. There seems to be a general impression that this will work out satisfactorily and will eliminate a great many of our lightning-arrester troubles, both theoretical and practical.

E. E. F. Creighton: In the matter of equivalent needle-gap of apparatus, resistance, etc., the mysteries are gradually clearing away. In measuring the equivalent needle-gap of a resistance there are a number of factors involved which give variations. The equivalent needle-gaps of rods in series and parallel are given below:

The *G* gap on the static machine was set at 4 in., the electrodes on the static machine were 1.4 in. in diameter. The inner coatings of three one-gallon Leyden jars were connected to each terminal of the machine, and the outer coatings of each set were connected to the resistance terminals. The equivalent needle-gap of three rods (750 ohms) was 1.59 in. With another equal resistance laid in parallel, the equivalent needle-gap was 1.27 in. With the third equal resistance laid in parallel, the equivalent needle-gap was 1.09 in. With the resistance short-circuited, the equivalent needle-gap was 0.15 in. If the three values of equivalent needle-gap of the three resistances are plotted, there is a proportionality which approaches a straight line. If we take into account the impedance in the circuit, we do not in this case get the concordant values shown later. There is every reason to believe that the same laws apply to a needle-gap used to measure voltage as apply to meters. In this case we are attempting to measure the impedance of a circuit 16 in. long with a needle-gap connected to leads which are more than three times as long, therefore we may scarcely expect to get correct values of the inductive drop across the 16 in. Furthermore, it requires a certain time to elapse after the potential is applied to the needle-gap before the gap begins to spark. If we put the needle-gap, as an instrument of measure, under better conditions of operation; that is, make the needle-gap circuit of less inductance than the circuit to be measured, it gives, at least in most cases, reasonably good results. Following is given the relation of the equivalent needle-gap of resistance made up in two ways:

1. As a sample rod of 250 ohms; 2. As seven rods in parallel and seven sets in series, making a total of 250 ohms. The equivalent needle-gap of the single rod was 0.47 in. (*G*-1 in). The equivalent needle-gap of the 49 rods was 0.86 in. The circuit composed of the 49 rods was necessarilly very much longer than that of a single rod, consequently a short-circuiting wire was laid over the same path and the equivalent needle-gap taken of the inductance. The value was 0.6 in. It will be seen that the equivalent needle-gap of the inductance and the equivalent needle-gap of the resistance will combine vectorially to make 88% of equivalent needle-gap of the impedance of the 49 rods. This error of 12% can be accounted for.

The same set of resistances was tested with a machine gap of $G = 7$ in. We obtained the following equivalent needle-gaps:

250 ohms in a single rod,	0.59 in.
250 ohms in 49 rods,	1.35 "
A copper wire in place of the 49 rods,	0.95 "

The combination of the resistance, 0.59 in. and inductance 0.95 in. vectorially gave 1.12 in. for the equivalent needle-gap of the 49 rods instead of 1.35 in. Again, the conclusion is that the discrepancy is within the degere of accuracy of measurement. These rods were made of standard composition with carborundum as a base. The resistance seems to have the same parelleling properties as metallic resistance. In fact, the same ohmic resistance of either non-metallic rods or metal wire gives the same equivalent needle-gap. There is a case, however, where parallel resistances made up of non-metallic composition will not have the paralleling properties. This kind of resistance may be placed in the category of coherers. If the substance of the resistance is composed of particles which are normally in separation and a static spark takes place, the particles cohere along a definite line and suddenly reduce the resistance to a comparatively low value. If the resistance is sufficiently reduced or the quantity of electricity is sufficiently small, the coherer thread of contacts relieves the potential, and there is no tendency for the material to break down in any other line. Under these circumstances, placing a parallel resistance in circuit will not affect the equivalent needle-gap.

As a matter of comparison, the equivalent needle-gaps are given herewith for rods of higher resistance. In each case the machine gap, *G*, was 4 in. The length of the rods in the following test was 8.5 in. The equivalent needle-gap of one 3200-ohm rod was 1.52 in. The equivalent needle-gap of two of these rods in parallel was 1.14 in. It should be noted that the equivalent needle-gap of this 3200-ohm rod is less than the equivalent needle-gap of 750 ohms, due to the fact that the three rods making up the 750 ohms gave a longer length of circuit than the one rod of 3200 ohms.

The equivalent needle-gap of one 220,000-ohm rod was 2.15 in. The equivalent needle-gap of two of these rods in parallel was 1.79 in. It should be noted in this test that the resistance of the rod as compared to the inductance of the rod is becoming predominant.

Since these results can be explained by conditions of the inductance, capacity, and the method of measurement, it would seem that an equivalent needle-gap taken under any other condition need only have all the conditions given to make it intelligible. If the frequency of the circuit is lowered the inductance factor in the above tests becomes more negligible.

The speaker has been working for several years on electrolyte cells, especially in their application to lightning-arresters. Two years ago one of these arresters was installed for test on a line during a short period, and last year we had an aluminum cell arrester on a 33,000-volt line during practically the whole lightning season. The speaker was scheduled last year to read a paper on this subject before the Institute, but it was thought advisable to put the arrester in commercial form with the experience of a season back of it before describing it. There is much to be said in its favor. We have collected a considerable amount of experimental data concerning its operation which we hope to present at the March meeting. These cells can be so made that the resistance above the critical voltage will be but $\frac{1}{10000}$ of the resistance below the critical voltage. In other words, a cell has a high resistance for normal potential, but a low resistance for potentials much above the normal. It has been our practice to install the arrester with its critical potential about 25% above normal. The current that this cell will discharge without increasing the potential to a dangerous value depends entirely upon the construction.

Below will be found some information regarding screening, chosen from tests on the multigap arrester. There were 190 $\frac{1}{32}$-in. gaps in series. Without a screen on the multigap arrester, the spark-potential on a 60-cycle circuit was 68 kv. With a screen around the multigap arrester, the spark potential dropped to 60.4 kv. With one terminal permanently grounded, the spark potential was 47.5 kv. without a screen; with a screen the spark potential rose to 53.9 kv. With one terminal arcing to ground and no screen, the spark potential was between 34 and 36 kv. Under the same conditions, with a screen, the spark potential was between 40 and 43 kv. It will be seen from these tests that the tendency is to make the spark potential more uniform for all conditions, but the screen does not entirely accomplish the result. The equivalent needle-gap with an impressed frequency of three million was then taken with the following results:

The equivalent needle-gap with the screen was 2.45 in.; the equivalent needle-gap without the screen was 2.67 in. The sum of the 190 series gaps is 6 in. The two halves of the arrester were connected by a wire of considerable length which makes the equivalent needle-gap higher than that of the normal installation.

In regard to the form of the potential wave. I presume that the direction of movement in Fig. 8 is from right to left and that a current transformer was used in getting the current record, but I cannot understand why the potential wave is all on one side of the zero value. Did not this oscillograph have a very low natural period of vibration? In Fig. 9 I note again that the deflections of the potential wave are greater on one side of the zero than on the other side, and that the generator wave of potential had already reached a considerable value before the switch was closed.

In Fig. 8 the oscillogram shows that the current apparently reversed in direction and then came gradually back to zero. Experience demonstrates that the current will continue to flow during most, at least, of the second half-cycle if it once gets started in the reversed direction. The false record of the oscillogram is due to the use of a current transformer. The magnetic leakage in the transformer prevents the current in the oscillograph rising to its true maximum value. The decreasing current is less sudden, the magnetic leakage less, and therefore the deflection is carried across the zero and returns along a logarithmic curve to zero.

H. B. Alverson: As the testing of lightning-arresters comes at the operating end, I can merely speak of certain results obtained in stations having 700- to 1200-kw. circuits, with a station capacity of 3,000 to 6,000 kw., with standard forms of lightning-arresters. The experience extended over a period of several years. It was soon found that arresters without series resistance on these circuits were of no value. The standard forms of lightning-arresters were used under ordinary conditions, with care and inspection, the limiting resistance producing a condition that gives operating results approaching continuous service. We have one of our stations equipped with choke-coils and low-equivalent arresters. With this outfit no interruption to the service has occurred; whether this covers all conditions or not of course we cannot tell. As Dr. Steinmetz has said, we cannot obtain arresters that will cover every condition, but it appears to me that on the lower voltages there is apparatus with which results may be obtained which will answer all purposes.

As I read it, this paper gives a method of determining the proper choke-coil to be used for any particular apparatus. With that data it should not be a very difficult matter to obtain proper proportions of apparatus so as to avoid suffering any severe interruptions except in extraordinary cases.

P. M. Lincoln: The collection of data on this subject of lightning protection is one of the most difficult with which the electrical engineer has to deal. It is difficult on account of th impossibility of observing what takes place in practice. It is impossible to tell the exact strength of the blow of the lightning force in any given case, and it is almost impossible to tell what its results are on account of the lack of observers at the time the thing happens and the varying tales one gets from casual observers after the thing happens. As I look at it, there are three methods by which we can collect data on the general subject. One is that just mentioned; viz., the observation of lightning phenomena themselves. This is unsatisfactory, for the reasons just stated. Although it is impossible, or difficult, rather, to judge of the reason why certain protective apparatus fails or succeeds in actual practice, still on its results in actual practice must depend the final judgment as to the value of that apparatus.

The second method of obtaining data on this subject is that of pure reason. In that category I place the first part of the paper read this evening, and also the interesting arrester arrangement which Mr. Mershon has just described. I would also place in the same category the very interesting exposition which Dr. Steinmetz has given us in regard to when a choke-coil is not a choke-coil. These things I would place under the head of pure reasoning on this subject, and we can get a good deal of information in that way.

The third way is to manufacture our own lightning and discharge it through set conditions in certain circuits, and by varying the conditions which obtain in the circuits, derive the information sought for. By creating our own artificial lightning and discharging it through given conditions, and making observations, by that method we can gain our most reliable data. That is the method pursued in the historical experiments by Oliver Lodge, as well as those pursued later by Mr. Wurts and still later by Mr. Thomas and others.

One more point, and that is in designing lightning apparatus we have two things to protect; one, the protection of the apparatus in the circuit; the other, the protection of the service. A simple spark-gap, nothing in series with it, is undoubtedly a most perfect protection to the apparatus. It allows the accumulated charge to get off the line, but at the same time it allows the dynamo current to follow and thereby interrupt the service, unless there is some arc-interrupting device. I think that these two things should be kept quite distinct: protection of the apparatus and the protection of the service. Most operating engineers will be willing to sacrifice some apparatus to save the service.

Ralph D. Mershon: Referring to the suggestions made by Dr. Steinmetz relatively to using a single resistance, I have preferred not to do this because it seems to me an advantage to have several paths, thus reducing the inductance as well as the resistance of the combined path to ground.

One reason for not using the number of gaps shunted in the way he described is that my experience with a series of gaps has not been a very happy one, due to the peculiar distribution of potential over these gaps by reason of capacity effects. I prefer something like a horn arrester which is not easily burned up, and is not subject to the uncertainties to which a series of gaps are liable. I am especially in favor of the horn arrester because it can be put out of doors; whereas a series of discharge gaps is not well suited to this.

I think that fuses on the line would not be effective in protecting station apparatus, judging from some things which have happened from time to time on transmission lines under construction. I have known of cases where a line in the course of construction, with the line conductor grounded at the point where the construction work left off, has been struck by lightning which, instead of going a mile along the line conductors to ground, has preferred to smash through insulators, presumably in the neighborhood of the point where the disturbance originated. I am sure that fuses, in order to protect the station, would have to be at closer intervals than those suggested by Mr. Thomas.

R. P. Jackson: Mr. Mershon asks about Fig. 4. In that case the static disturbances were impressed upon both ends of the transformer. I left off the other end of the curve, as it was a duplicate of the end shown. We got no record different from the end which is shown. As to what the effect of the disturbance on one end would otherwise have been on the other we cannot tell; but tests have been made with transformer coils, with iron and without iron, showing no material difference, in choking effect, etc.

In regard to oil choke-coils, and the closer spacing of the turns, another point I did not mention was that this choke effect is not directly a function of its total inductance, but of its inductance per unit length; and naturally a coil which could be made more compact and have greater inductance per unit length of wire would have a greater reflecting effect. It is true, as Dr. Steinmetz pointed out, the capacity effect would come in, and a coil would be ineffective for very high frequency and very low frequency, but there is a wide range which appears to include most lightning disturbances which a choke-coil will handle.

Regarding the 400 ohms as a critical resistance, it was not meant that this was the only permissible resistance without any question whatever. It was a value which, under the conditions given, would just eliminate a rise of potential and reflection at the lead of the apparatus, meaning that lower resistances were desirable, if possible. Therefore, from that calculation it appeared to be that 100 ohms, or something in that region would be more desirable than anything above it. It would not mean that 1,000 ohms would not do any good, but that it would do so little good that great effort should be made to keep below the 400 ohms, because, under the conditions indicated, using 1,000 ohms ,while there is some discharge, there is still a rise of potential and reflection which will do harm. While the rise of potential is not the same for any resistance whatever, still it would be there to some degree; 400 ohms would prevent rise of the deflection, but still give a rise equal to that of the original incoming wave, while with zero resistance there would be no potential whatever existing there. What Mr. Thomas says about parallel lines requiring lower resistance is perfectly true.

In regard to the oscillograms, I did not operate the oscillograph at the time the records were taken, and I cannot say why the one on Fig. 8 is not symmetrical, but any one who has worked with an oscillograph knows that they do become erratic at times and deviate considerably, probably due to static influences.

This effect is not so noticeable on Fig. 9, but still the curve is somewhat distorted, due to some lack of adjustment in the oscillograph, or failure to ground the frame.

J. F. Vaughan (by letter): In view of recent progress made in special devices for the protection of lines and apparatus there seems to be good prospect of accomplishing proper protection against ordinary disturbances due directly to internal or induced by external causes. Little attention, however, has been given to the possibility of protecting lines against direct lightning stroke. It is unreasonable to expect to provide sufficient line insulation to prevent such a stroke from going to ground, or sufficiently frequent arresters safely to carry the excessive charge to ground. Why not divert such strokes from the lines? Lightning rods on the line poles and overhead grounded wires have been of some value in preventing damage to lines and poles. Why not go a step farther and provide entirely separate paths to ground by means of lightning rods mounted on separate poles well above and at one side of the line. With this in view, the 50,000-volt Taylor's Falls transmission line in Minnesota, in addition to a number of other devices, was protected last summer for two miles through the most exposed region by poles at the side of the line carrying rods 25 ft. above the upper transmission wire.

Fig. 1.

Although the storms last summer were unusually few and light, the photograph of one direct stroke to earth shows the main discharge branching off into many secondary discharges like an inverted tree, covering an area of ground of probably over a mile in diameter, indicating clearly that the territory affected was not restricted to the immediate vicinity of the bolt. It is interesting to note that while six transmission line poles in different parts of the line were splintered the previous summer before any wire was strung, last summer several of the lightning-rod poles showed punctured tell-tale papers inserted in their ground connections, one puncture indicating a heavy discharge to ground, while the line itself, though not in operation, did not suffer.

A. Henry Pikler (by letter): The present paper, it seems to me, although its title in general refers to lightning protective apparatus, deals in reality with such elements of it as are protective not against lightning directly, but rather against its secondary effect—induced high potentials; still more efficiently against surges due to short circuits, sudden and great changes of the line current. Furthermore, this apparatus is suitable to protect only particular points of an electric power transmission equipment—namely, those located in the power house or in the sub-station and not the transmission line.

In discussing the devices brought forward in the paper, I shall restrict myself to the choke-coil. Of late the choke-coil appears to have been much neglected. I have seen large power installations in connection with a 35,000-volt, 30-mile transmission line, made by one of the leading manfacturing companies of the country, where the choke-coil was omitted. The consequence was that during lightning storms, or, in the case of grounds, sudden changes of loads, short circuits, the ensuing surges ruptured the insulation of the main switches in the power house and grounded the line, although the lightning-arresters were discharging profusely.

In order to illustrate the powerful protection offered by a few turns receiving tremendous shocks directly, I want to mention that in the same power plant one of the little synchronizing transformers on the auxiliary bus-bars was connected up in the wrong way and when two transmission lines were to be paralleled, this was done in full oposition of the operating generators. A tremendous short circuit and rise of potential was the result and almost all the transformers broke down. Upon investigation it was found that only the very first turns of the end-coils were punctured through many small holes. It will be interesting to note that these end-coils had very heavy insulation on them, (also the end-turns were extra heavily insulated) sufficient to stand about 100,000 volts (though they were not at all intended to be choke-coils), whereas the other coils, many in number, were almost bare. These latter were entirely uninjured.

I was very much surprised to hear Mr. Mershon, the chairman of the High-Tension Transmission Committee, recommend the use of the first few turns of the transformer as a choke-coil by placing extra heavy insulation on them, thus saving the expense of an extra choke-coil. While theoretically this seems plausible, from the practical standpoint I most decidedly disagree with him. The duty of the protective apparatus is to save from injury the vital elements of a transmission equipment, even at the cost of life of the protective apparatus. This is necessary for two reasons: to avoid interruption of the service, and to save the more expensive power station equipment from break-downs and burn-outs.

To have the choke-coil form the internal part of the transformer would mean to provoke just this trouble. There exists no commercial insulation or method of insulating that would save the choke-coil from a flash-over and ensuing burn-out between adjacent layers and turns, if the relation between inductance and capacity of coil and the periodicity of the disturbance is such as to cause resonance. Such and similar disturbances would mean to cut out that transformer and cripple the service for some time. Besides this, it means damaging and repairing a piece of apparatus worth several thousands of dollars, whereas if the choke-coil is made independent of the transformer it means only the damage of the choke-coil, worth perhaps a few hundred dollars.

Furthermore, from the standpoint of the designing engineer I do not consider it reasonable to have two pieces of apparatus, serving different purposes and involving entirely different methods of calculation, design, and manufacture combined in one. Both would suffer in the end, the transformer as well as the choke-coil. At the same time I do believe and strongly recommend the insulating of the first few turns next to the line with special care and precaution on every piece of apparatus, but I would like to see the choke-coil in series with it. On high-voltage induction motors operating at 5,000 volts and above, break-downs used to be very frequent, and there seemed to be no insulation good enough to resist potential rises due to sudden variations in load, etc.; the choke-coil was put in series with the terminals, and the trouble was eliminated at once.

H. W. Buck (by letter): The tendency of this paper and its discussion, which is common in the treatment of lightning disturbances, is to regard the problem solely from the standpoint of the mathematical theory of oscillations. This is undoubtedly wise to a certain extent, but there are very important lightning troubles which lie quite outside the realm of calculation. I refer particularly to direct strokes upon a transmission line from lightning bolts of great violence. Here the problem before the engineer might be considered more one in fortifications than in oscillations or surges. There are many discharges which take place in thunderstorms between clouds and earth which apparently are not only of very high potential but also of very large current volume. Trees and poles are sometimes completely shattered by such strokes. The explosive violence with which wood-fibre flies to pieces at such times seems only explicable on the theory that there is sufficient current to cause either instantaneous evaporization of the juices in the wood and consequent expansive force, or else the immediate expansion of the gases held in the pores of the wood. In either case the volume of current must be very large, and the ordinary lightning-arrester resistances used for the discharge of transmission lines is entirely inadequate. My feeling is that the electrolytic arrester described in the paper, if selected for the ground path of one of the above lightning bolts, would meet much the same fate as that of the tree.

The most promising system of protection against direct strokes on the line seems to be that of the overhead ground wire, or preferably a grounded network supported on the transmission poles or towers above the conductors. Such a system if properly installed and grounded at every support should afford almost complete protection against the striking of transmission conductors or insulators. If more than one ground shield wire is used, and the two or more wires are connected together electrically at frequent intervals, a further protection is provided, at least part, by this short-circuiting shield against the induced disturbances in the conductors from neighboring lightning discharges.

There is another source of disturbance from lightning which is not usually referred to in discussions of lightning troubles. I have known of a number of instances where direct strokes upon objects such as trees immediately adjacent to a line have been followed by a simultaneous short-circuit between phases on the transmission line at that point. Such action may be explained on the theory that the air surrounding the conductors becomes ionized and conducting by the influence of the stroke near by. Those who have handled high-voltage switches without barriers between them have observed how easily a short-circuit is started in a similar way by the influence of a neighboring arc. Lightning trouble of this kind cannot be prevented by the ordinary type of ground-discharge arrester.

Deductions as to the suitability of various types of lightning-arresters from the experiences of individuals are very misleading. One man who has had no lightning trouble during a season attributes his success to the particular type of arrester he has installed in his plant. His success quite possibly might have been the same with no arrester at all on his lines. Another operator whose arresters have been completely destroyed, probably by some direct stroke on the line, discards the type as useless although it may have successfully taken care of all ordinary disturbances.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

REPORT OF LIBRARY COMMITTEE.

We beg to submit herewith a report of the present state of the Library of the INSTITUTE, and the state of the several funds under the cognizance of this Committee.

As in the preceding two years, progress in extending the Library collections has practically been halted, owing to precedence being given to the canvass for raising funds from the membership to meet obligations assumed in connection with the United Engineering Building. It is hoped by the time the Library is installed in its splendid quarters in this building, your Committee will again have a free hand to proceed with its work in building up the collection—a work commenced in 1901 and interrupted two years later.

During the year the Library received from the International Electrical Congress of St. Louis, 1904, a fund of $2 052.67, representing the profits derived from the sale of Transactions of the Congress. In accordance with the Deed of Gift, the annual proceeds of this fund is to be devoted solely to the purchase of international electrical literature.

The Bibliography of the Wheeler Gift, which has been under preparation the past four years, is now complete, and within a few weeks the manuscript will be placed in the hands of the printer. The preparation of this work, which includes bibliographic annotations to more than 5 000 titles of books and pamphlets, represents a vast amount of labor on the part of Brother Potamian, to whom a great debt of gratitude is due for the scholarly and exhaustive manner in which he has acquitted his arduous task. The work will form a large octavo volume, and will undoubtedly take high rank in the literature of bibliography. According to the Wheeler Deed of Gift, every member of the INSTITUTE will be entitled to a copy.

During the year a copy of the catalogue of the periodicals in the Library was sent to every member of the INSTITUTE, together with a circular asking the aid of the members in filling out incomplete sets of publications, noted in the catalogue and circular. We regret to report that the appeal received less than a half-dozen favorable responses.

During the year gifts of books, pamphlets and periodicals were received from the following:

ADAMS, EDWARD D.
ANDREWS, L.
ASTOR, COL. J. J.
ALLEN, W. F.
ASSOCIAZIONE ELET. ITAL.
BETHELL, U. N.
BYLLESBY, H. M.
CARTY, J. J.
COLUMBIA UNIV.
DEVINNE, T. L.
DOREMUS, C. A.
ECLAIRAGE ELECTRIQUE.
EDMUNDS, C. K.
GAUTHIER-VILLARS.
GERARD, L.
GODDARD, C. M.
IRON & STEEL INST.
JENKS, W. J.
LIBRARY OF CONGRESS.
MCGRAW PUBLISHING COMPANY.
MARTIN, T. C.
MULOCK, SIR WM.
NATIONAL PHYS. LAB.
N. Y. CITY COM. ON ELEC. LIGHTING
PEDERSON, F. M.
PLASS, J.
POLYTECHNIC INST., BROOKLYN.
RIES, E. E.
ROSENTHAL, L. W.
SCHEFFLER, F. A.
SPRAGUE, F. J.
STEVENS, J. F.
THURSO, J. W.
WARD, G. G.
WEAVER, W. D.
WEST SOC. ENG.
WOODBURY, C. J. H.

Following are the statistics of the Library, brought up to May 1, 1906:

STATISTICS OF LIBRARY.

Source.	Titles.	Volumes.	Pamphlets	Valuation.
Report of May 1, 1905	7219	10204	392	$21,244.31
PURCHASES:				
Carnegie Fund	7	98		76.02
Donation Fund	36	44	99	92.05
Mailloux Fund	4	7		37.45
Institute Appropriation	3	7		26.00
Periodicals	74	184		368.00
GIFTS:				
W. J. Johnston				75.00
Edward D. Adams	3	8		53.93
College of Science, Imperial Univ., Japan	1	19		38.00
Miscellaneous Gifts	53	146	24	58.55
Total, May 1, 1906	7400	10717	515	$22,069.31
Duplicates	228	609		824.74
Duplicate Periodical Titles	80			
	7092	10108	515	$21,244.57

Following is the total valuation of the Library on May 1, 1906, including permanent Library fixtures:

TOTAL VALUATION.

Books	$22,069.31
Book Stacks	1,470.25
Furniture, Catalogue Cases, etc	135.20
	$23,674.76

Following are tabulations giving the present state of the several funds of which the Library Committee has cognizance:

Donations (General Library Fund).

Dr.		Cr.	
Balance May 1, 1905	$315.31	Purchase of books	$92.05
Interest May 1, 1906	9.30	Unexpended	232.56
	$324.61		$324.61

Carnegie Fund.

Dr.		Cr.	
Balance May 1, 1905	$4,082.37	Wheeler Bibliography	$251.50
Interest May 1, 1906	121.50	Unexpended	3,952.37
	$4,203.87		$4,203.87

Mailloux Endowment Fund. ($1,000.)

(Proceeds for the maintenance of certain sets of periodical publications.)

Dr.		Cr.	
Balance May 1, 1905	$8.20	Books and Binding	$14.25
Interest May 1, 1906	30.00	Subscription	23.20
		Unexpended	.75
	$38.20		$38.20

Internat'l Elec. Congress of St. Louis, 1904, Fund. ($2052.67)

(Proceeds for the purchase of international electrical literature.)

Dr.		Cr.	
May 1, 1906	———	Unexpended	———

The table below gives an account of funds appropriated by the Institute for Library purposes during the past year:

Institute Appropriations.

Dr.		Cr.	
Appropriation for Maintenance	$3,000.00	Rent	$1,475.04
Sales of Periodical Catalogue	51.25	Insurance	106.35
		Salary, Librarian	765.00
		Binding	154.15
		Library Supplies	29.62
		Subscriptions	26.00
		Express and Postage	91.34
		Miscellaneous	12.20
		Distributing Periodical Catalogue	34.74
		Unexpended	356.81
	$3,051.25		$3,051.25

Following is a comparative statement of disbursements from the annual appropriations of the past three years:

	1903-1904	1904-1905	1905-1906
Rent	$1,505.04	$1,475.04	$1,475.04
Insurance	54.77	106.35	106.35
Salary, Librarian	780.33	780.00	765.00
Extra Assistance	50.00	54.00	———
Binding, Periodicals and Books	254.20	277.75	154.15
Library Supplies	65.36	16.51	29.62
Subscriptions	20.00	32.00	26.00
Express and Postage	11.35	14.60	†126.08
Miscellaneous	7.70	*109.35	12.20
Unexpended	251.25	384.40	356.81
Appropriation	$3,000.00	$3,250.00	$3,051.25

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* Includes $101.25 for printing Catalogue of Periodicals, for which an extra appropriation of $250.00 was made.

† Includes expense of distributing Catalogue of Periodicals to members.

The Library Committee,
W. J. Jenks.
F. A. Pattison.
F. W. Roller.
C. A. Terry.
W. D. Weaver, Chairman.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1906.

The Board of Directors presents herewith for the information of the INSTITUTE a report of its work during the past year, also of the financial standing of the organization.

The Annual Convention was held at Asheville, North Carolina, June 19–23, 1905. The total attendance was approximately 225. At this Convention, President Lieb delivered his annual address, and about 25 engineering papers were read and discussed. Arrangements are now nearing completion for the 1906 Convention, which will be held at Milwaukee, May 28–June 1. An excellent program of high-grade papers has been prepared, and a large attendance is anticipated.

During the year the Board of Directors has held twelve regular monthly meetings. Abstracts of most of the annual reports of the principal committees are included herewith.

The total membership now is 3870, an increase during the year of 410. The number of students enrolled is 618.

In June, 1905, the Board of Directors received a communication from the New York Edison Company, offering the INSTITUTE the use of the auditorium in their building at 44 West 27th Street, New York, for holding the monthly INSTITUTE meetings, until the United Engineering Building is completed. This courtesy was promptly accepted by the Board, and meetings have been held at the above address commencing in September, 1905.

A communication was received in November, 1905, from the Institution of Electrical Engineers of Great Britain, extending an invitation to the members of the INSTITUTE to visit London and vicinity, in June, 1906. This invitation has been accepted, and arrangements are now being made by a number of our members to participate in this trip.

An invitation was also received from the Italian Electrotechnical Association, inviting the INSTITUTE to visit the Milan Exposition and other places in Italy, during June, 1906; but after communicating with the membership it was found that the number who signified their desire to attend was too small to warrant the INSTITUTE being officially represented, and consequently the Italian trip has been postponed to a future season.

The International Electrical Congress of St. Louis, 1904, through its President, notified the INSTITUTE in February, 1906, that the Congress had decided to offer the INSTITUTE the balance remaining in the hands of the Congress treasurer, as a gift to the INSTITUTE in the form of a separate fund to be invested by the INSTITUTE; the proceeds to be expended in the purchase of international electrical literature for the INSTITUTE library. This gift was formally accepted by the Board, and resolutions adopted to the effect that the fund shall be known as the "International Electrical Congress of St. Louis, 1904, Library Fund." This fund, which now amounts to $2067.06 has been deposited in a Trust Company under the conditions indicated above.

In March, 1906, the Board directed that the resolutions adopted by the Standardization Committee in favor of the Metric System, be submitted to the membership for a letter ballot, and that the Congressional Committee in charge of the pending bill relating to the Metric System be notified. The result of this ballot was 1569 in favor and 178 against the resolutions.

Board of Examiners.—Twelve meetings of this Board have been held during the year at which applications for election as associates, enrolment as students, and transfers to the grade of member have been reported to the Board of Directors as follows:

Recommended for election as Associates	574
Not recommended for election as Associates	5
Recommended for enrolment as students	310
Recommended for transfer to grade of Member	41
Not recommended for transfer to grade of Member	23
Held for further information	8
Total applications considered	961

Committee on Local Organizations.—As this Committee was appointed the latter part of March, 1906, it has had no opportunity for shaping or assisting in the work of the branches during the past year. A circular letter has been sent to the various local organizations asking for reports and suggestions which may be useful to the Committee in promoting the welfare of the branches and in proposing to the Board of Directors such measures as may be found desirable.

The reports from the branches to the Secretary's office during the past year have been epitomized in the monthly PROCEEDINGS. A review of these reports shows that the activity is quite general. Many of the branches report original papers. On the whole, the condition of the branches as indicated by these reports, is a healthy one.

A general summary shows that there are now twenty-one active centers; several in a state of semi-activity; and three or four which are dead, or practically so. Several places where life has died out have been characterized by change of local conditions; from some of the places the active men have moved away.

The sum total of activity in the branches during the past year will measure a very considerable proportion of the total interest and activity among INSTITUTE members as a whole. The development of th

INSTITUTE as a national body, will be greatly strengthened and promoted as the branches, particularly those in the leading cities, come to the recognized as the established local electrical societies of those centers.

United Engineering Building.—The contract for the building was awarded to Wells Brothers Company. Construction work began the latter part of last summer. The progress report of the Superintendent dated April 23, 1906, is as follows:

Number of workmen, 400; walls up to thirteenth floor; terra-cotta floors to roof; steel work finished; plumbing and electric risers up to the fifth floor; heating up to the sixth floor; metal lathing started; boilers set; partitions will start this week; work progressing very rapidly.

A pamphlet containing the plans of the building and a general statement by the Building Committee has been issued.

The United Engineering Society is now in communication with a number of engineering bodies with a view to their becoming associate societies, occupying space in the building.

Building Fund Committee—The last annual report stated that $66,534.50 had been pledged in subscriptions to the Land and Building Fund, and that $19,301.25 had been paid in and deposited to the credit of the Fund. The chairman of the Committee reports that on April 30, 1906, the subscriptions had reached a total of $132,434.30 from 644 subscribers and that $88,238.10 had been received and deposited. Among the larger new subscriptions were $5,000 from Mr. C. A. Coffin, and $5,000 from Mr. Clarence W. Mackay; $25,000 from the General Electric Company, and a joint subscription of $25,000 from the American Telephone and Telegraph Company; the Western Electric Company; the New York Telephone Company and the New York and New Jersey Telephone Company. Subscriptions are promised by other electrical manufacturing and public service corporations, while the canvass is also being carried on actively amongst the individual members; with the prospect of a steady growth in the amount raised. The publication of the plans for the United Engineering Building has been a decided stimulus to the generosity of the profession, and the Committee entertains hopes that the completion and occupancy of the building will enable it to announce the securing of the entire $200,000 desired for the purpose of paying the quota of the INSTITUTE for the land and installing it appropriately in the new home.

Committee on Finance.—In addition to the special funds already reported, there has been established the "International Electrical Congress of St. Louis Library Fund," which was given to the INSTITUTE by the Executive Committee of the Congress upon closing up its affairs. The interest from this fund is to be devoted solely to the purchase of foreign electrical literature. The ordinary receipts during the fiscal year were $49,423.43; the ordinary disbursements, $40,767.22; and the net cash gain was $8,656.21.

The bank balance available for current expenditures on April 30, 1906, was $14,979.09. Adding to this sum the market value of the United States bonds owned by the INSTITUTE, $8,320, makes a total of $23,299.09 in cash or its equivalent, immediately available. Under the Founders' Agreement with the United Engineering Society, the INSTITUTE is pledged for its share of the cost of the land upon which the United Engineering Building is being erected. This share of indebtedness is $180,000, upon which 4% interest is being paid from the Building Fund. The principal is due in twenty annual payments; and it is to this purpose that the Land, Building, and Endowment Fund is to be devoted; and assessments of the United Engineering Society have been paid out of this Fund. The advance payment of about one-quarter of the principal, is now under consideration

Standardization Committee.—This Committee has held four meetings and will hold one or two more before the summer. The principal work undertaken was the revision of the Committee's former report, which in the future it is proposed to call " Standardization Rules of the A.I.E.E."

This revision includes the correction and rearrangement of old matter, the introduction of new definitions and classifications, and recommendations regarding new apparatus and new conditions. After the Committee finally passes upon the revised rules, they will be submitted to the various manufacturers and engineers interested, for suggestions and criticisms. Then after further consideration by the Committee the Rules will be referred to the Board of Directors. It is hoped that the result will be a set of Rules generally acceptable and permanent for some years to come.

It is proposed to incorporate with the Rules certain appendices, such as Copper Wire Resistance Table, Specifications for Testing Rubber Covered Wires, Notation, and other matters related to standardization.

In accordance with the resolutions passed at the International Electrical Congress, St. Louis, 1904, the British Institution of Electrical Engineers, acting as organizer, has secured the appointment of national delegates from various countries and arranged for a meeting to be held in London the latter part of June. The Committee is in favor of standardizing certain general features and methods in connection with electrical apparatus in regard to which it is hoped that international agreement can be secured.

Committee on Papers.—Arrangements were made for the holding of eight regular monthly meetings at which were presented 17 papers. The total registered attendance on these meetings was 1,527, that is an average attendance per meeting of 192. Besides the authors, 57 members participated in the discussion of the papers. Arrangements have also been made for the presentation of twenty papers at the Annual Convention to be held at Milwaukee during the last week of May.

The Editing Committee.—During the last twelvemonth there have been edited and printed under the direction of this Committee approximately 1050 pages of Proceedings, composed of 850 pages of papers, and 190 pages of discussion. Volume XXIII, of the Transactions—January 1, to December 31, 1904—containing approximately 838 pages (503 pages of papers and 335 pages of discussion) was issued to the members June 28th, 1905. Volume XXIV of the Transactions—January 1st, to December 31st, 1905—containing approximately 1150 pages, (940 pages of papers, and 210 pages of discussion) is now in press, and will be delivered in July to such Associates and Members as have paid their dues for the current fiscal year, ending April 30th, 1907, as provided in the by-laws.

Edison Medal Committee.—On July 24, 1905, the sub-committee on Institutions of Learning reported that of the institutions which had asked to be placed on the eligible list, fifty-one (51) had been found qualified. The report of the sub-committee was approved by the Medal Committee. On Aug. 4, 1905, a circular letter was sent to these fifty-one institutions advising them of the action of the Committee and requesting that they present competitors for the year 1905. Acknowledgements were received from representatives of eleven institutions; none of them presented theses for 1905 although several stated that they hoped to do so another year.

In accordance with the recommendations of the sub-committee on Institutions of Learning the Medal Committee has added four more institutions to the eligible list, making the present total 55.

A circular letter dated January 6, 1906, and a copy of the By-Laws were mailed to each institution on the eligible list, urging that competitors be presented for 1906. Two copies of a form of presentation notice to be used in presenting competitors accompanied each circular letter. As these notices cannot be sent in until after the men have received their degrees, none have been received up to the present time.

John Fritz Medal.— The John Fritz Medal for 1905, was awarded to George Westinghouse by the John Fritz Medal Board of Award, upon which the INSTITUTE is represented.

Committee on Law.—This Committee has held several meetings during the year for the purpose of considering all matters referred to it by the Board of Directors. The principal matter referred to the Committee was the revision of the Constitution and By-Laws. A circular letter was sent to the membership asking for an expression of opinion in regard to the modifications and improvements deemed desirable in the present Constitution. All suggestions and criticisms received were considered in detail. A report including a draft of proposed revised Constitution was then formulated and submitted to the Board of Directors and subsequently to the membership for letter ballot.

The Committee has availed itself of the authority granted it by the Board to consult the legal counsel of the INSTITUTE whenever necessary.

Committee on Forest Preservation.—The Committee after examining the Constitution and By-Laws of various forestry associations, concluded that it would be inadvisable to recommend that the INSTITUTE accept any of the invitations for joint action regarding forest preservation.

So far as forest preservation for the benefit of the electrical industry is concerned, forest fires are of fully as great importance as the effect on the lumber industry and consequently the members of the INSTITUTE should be urged to aid in making effective the laws for the control of forest fires. The Committee also recommends that special instructions be given to employees by companies operating water power plants and transmission lines that any aid given by their employees in checking such fires is directly beneficial to these companies.

The Committee is convinced that the forestry work that will be most beneficial to the electrical industry is such as will prevent washing away of the land along the banks of the streams, and it is recommended that hydro-electric companies consider the advisability of obtaining from the government or from a committee of the INSTITUTE instructions for the preservation of slopes by planting bands of trees or shrubs at such points as will tend to accomplish this result. If a considerable portion of these trees be chestnut or locust a supply of poles and pins may be obtained therefrom in the future, thereby directly benefiting the companies for their efforts. In order to attract the interest of farmers living on the water sheds of streams it will be necessary to aid them by furnishing additional information and instructions. This subject so far as the Committee can ascertain has not been taken up by any of the forest associations, although it is apparent that the Agricultural Department is endeavoring to aid in the matter.

Membership.—The total membership at the close of last year's report was 3460, classified as follows:

Honorary Members		2
Members		482
Associates		2976
Total May 1, 1905		3460
Elected prior to May 1, 1905, and since qualified		103
Elected May 1, 1905, to April 30, 1906, and qualified		464
Restored to Membership		2
		4029
Deduct—		
Total Deaths	20	
Total Resignations	42	
Dropped as delinquents	97	
		159
Total membership April 30, 1906		3870

The membership April 30, 1906, is classified as follows:

Honorary Members	2	
Members	508	
Associates	3360	
Total		3870

Associates Elected.—The Associates elected during the year, May 1, 1905, to April 30, 1906, and their present status is as follows:

Qualified and now Associates	464
Elections cancelled	5
Not qualified on April 30	122
Total elections	591

Resignations.—The following Members and Associates have resigned in good standing during the year:

Members.—Alex. Macfarlane.

Associates.—F. Ramsey Allen, John A. Campbell, C. Weston Clark, J. U. Clarke, A. Fredk. Collins, Erik Cronvall, Walter S. Dix, R. R. Dunlop, J. D. Foy, W. R. Gardener, H. W. Goddard, H. F. Gurney,

R. H. Hadfield, M. L. Holman, D. A. Holmes, Wm. A. Hopkins, C. E. Hyatt, H. L. Johnston, F. M. Jourdan, H. C. Judson, J. C. Kelsey, F. K. Knowlton, Chas. LeBlanc, Jos. N. LeConte, W. S. Mallory, C. R. Metchear, Benj. H. Moore, G. G. Morse, A. E. Payne, J. B. Riddle, E. B. Rich, A. Wm. Schramm, F. B. Spencer, H. T. Stewart, A. B. Storms, Jos. S. Stout, W. C. Temple, G. H. Thomson, A. L. Tucker, Frank W. Walker, W. J. Wilgus. Total, 42.

Deaths.—There have been during the year the following deaths:

Members.—J. C. Chamberlain, Chas. Cuttriss, F. A. LaRoche, E. A. Leslie.

Associates.—F. A. Churchill, Jr., F. E. Cooley, W. W. Donaldson, Geo. W. Davenport, E. C. Dobbelaar, W. E. Gavit, Guthrie Gray, J. H. Hamilton, C. H. Hines, W. B. Rankine, Henry Rustin, Theo. Spencer, I. A. Taylor, H. S. Webb, S. B. Winchester, H. R. Wellman. Total, 20.

The average receipts and disbursements *per capita* for the past six years, is shown in the following table:

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past six years.

Year	1901	1902	1903	1904	1905	1906
Membership	1260	1549	2230	3027	3460	3870
RECEIPTS PER MEMBER:						
Entrance Fees	$0.61	$1.16	$1.59	$1.65	$0.83	$0.75
Dues	8.61	10.06	9.01	9.33	9.30	9.47
Transactions, Sales and Advertising	1.03	1.54	1.79	2.11	1.70	2.15
Badges	.18	.26	.35	.39	.28	.27
Interest	.12	.24	.21	.18	.21	.13
	$10.55	$13.26	$12.95	$13.66	$12.32	$12.77
DISBURSEMENTS PER MEMBER:						
Transactions	$2.83	$3.50	$4.67	$3.43	$3.77	$3.33
Salaries	2.49	2.78	2.49	2.50	2.20	2.64
Meeting Expenses	1.05	1.13	.87	1.16	.82	.68
Rent	.94	.94	.65	.79	.75	.68
Library, including Rent and Salaries	.55	1.85	1.38	1.39	.81	.69
Postage	.46	.51	.69	.66	.66	.58
Stationery and Miscellaneous Printing	.39	.53	.96	1.01	.70	.78
General Expenses	.33	.59	.52	.45	.54	.29
Badges	.16	.19	.27	.35	.25	.22
Express	.15	.15	.15	.28	.22	.23
Advertising						.36
Total	$9.35	$12.17	$12.65	$12.02	$10.72	$10.48
Credit Balance per Member	$1.20	$1.09	$0.30	$1.64	$1.60	$2.29

GENERAL FINANCIAL STATEMENT AS APPROVED BY THE BOARD OF DIRECTORS MAY 14, 1906.

May 14, 1906.

DR. SCHUYLER S. WHEELER, PRESIDENT OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, NEW YORK CITY.

Sir: Pursuant to the provisions of the Constitution, the Committee on Finance has during the year exercised supervision over the financial affairs of the Institute. It has considered all bills and approved for payment such as constituted a proper charge against the Institute.

It has considered and reported upon specific appropriations, and has made special reports upon various matters referred to it by the Board of Directors.

As provided by the Constitution, it has employed an expert accountant to audit the accounts of the Institute; and this report made by Messrs Peirce, Proud & Co., certified public accountants, has been approved by the Board of Directors, and is transmitted herewith.

Very truly yours,

J. J. CARTY, *Chairman Committee on Finance.*

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15 Dey St., NEW YORK, May 12, 1906.

MR. JOHN J. CARTY,
Chairman Committee on Finances.

DEAR SIR:

In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1906.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance sheet April 30, 1906.

Exhibit B. Receipts and disbursements for general purposes for year ended April 30, 1906.

Exhibit C. Receipts and donations for designated purposes, also expenditures on same for year ended April 30, 1906.

Exhibit D. Condensed cash statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,

PEIRCE, PROUD & CO.,

Certified Public Accountants.

40 Cedar St., New York, May 12, 1906.

Mr. John J. Carty,
Chairman Committee on Finance.

Dear Sir:

Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30th, 1906, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30th, 1906, and that the accompanying statements of Cash Receipts and Disbursements are correct.

Peirce, Proud & Co.,
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Balance Sheet, April 30, 1906.

Exhibit A.

Assets.		
Cash:		
Land Building and Endowment fund	$80,700.62	
Carnegie (Library) fund	3,952.37	
General Library fund	232.56	
Compound Membership fund and interest	4,886.97	
*Mailloux fund	1,000.75	
International Electrical Congress of St. Louis, 1904, Library fund	2,067.06	
	$92,840.33	
*General cash in bank	14,978.34	
Secretary's petty cash on hand	500.00	
		$108,318.67
U. S. Govt. bonds 3s, 1918	8,000.00	
Premium on bonds (market value)	320.00	
		8,320.00
Library volumes and fixtures	23,674.76	
Transactions	3,936.75	
Congress books	318.75	
Office furniture, fittings, etc	3,187.90	
Badges	112.25	
		31,230.41
Accounts Receivable:		
Members for past dues	6,470.35	
Members for current dues	65.00	
Members for entrance fees	105.00	
	$6,640.35	
Miscellaneous	186.95	
Subscriptions	41.40	
Students' dues	72.00	
For advertising	1,662.49	
		8,603 19
Total Assets		$156,472 27

Liabilities and Surplus.		
Funds:		
Land Building and Endowment fund	$80,700.62	
Carnegie (Library) fund	3,952.37	
General Library fund	232.56	
Compound Membership fund and interest	4,886.97	
Mailloux fund	1,000.75	
International Electrical Congress of St. Louis, 1904, Library fund	2,067.06	
Reserve fund (U.S. Govt. bonds)	8,320.00	
Total liabilities		$101,160.33
Surplus:		
In cash	$15,478.34	
In property and accounts receivable	39,833.60	
		55,311.94
Total liabilities and surplus		$156,472.27

* The Farmers' Loan and Trust Co. deposit account includes 75c. of the Mailloux Fund.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1906.

EXHIBIT B.

RECEIPTS.

Entrance fees	$2,902.00	
Current dues	31,766.30	
Past dues	2,352.00	
Advance dues	319.00	
Students dues	1,830.00	
Transfer fees	300.00	
Badges	1,040.00	
		$40,509.30
Sales Transactions	$964.04	
Subscriptions, Proceedings	560 75	
Advertising	5,699.60	
Electrotyping and Engraving	21.45	
Binding	89.25	
Exchange	19.09	
Interest on U. S. Govt. bonds	240.00	
Interest on bank balance	248.73	
Interest on Life Membership fund	86.97	
Royalty	180.00	
Library account	25.60	
Sundry amounts received from accts. written off or carried in suspense	465.62	
		8,601.10
Total		$49,110.40

DISBURSEMENTS.

Stenographers and Typewriting	$88.14	
Stationery and Printing	2,938.75	
Postage	2,246.87	
General expenses	1,068.11	
Meeting expenses	875.55	
Branch meetings	1,762.09	
Badges	881.76	
Salaries	8,211.07	
Electrotyping and Engraving	1,723.89	
Publishing Transactions, Printing, Binding, etc	9,843.39	
Salary	2,000.00	
Rent	2,645.01	
Binding	1,320.03	
Express	883.72	
Office furniture	192.50	
Advertising commissions	1,376.91	
		$38,057.79
LIBRARY:		
Rent	$1,475.03	
Librarian's salary	780.00	
Library insurance	106.35	
Miscellaneous	313.31	
		2,674.69
Profit and loss on % Library		34.74
Total		$40,767.22
Excess of receipts over disbursements, deposited in General fund	8,256.21	
Deposited in Life Membership fund	86.97	
		8,343.18
		$49,110 40

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1906.

EXHIBIT C.

RECEIPTS.

Land, Building and Endowment fund, Donations, Interest, etc	$69,549.46
General Library Fund, Interest	9.30
Carnegie (Library) Fund, Interest	121.50
Mailloux Fund, Interest	30.00
International Electrical Congress of St. Louis, 1904, Library Fund	2,067.06
Life Memberships to Fund	400.00
	$72,177.32

EXPENDITURES.

Land, Building and Endowment Fund, paid United Engineering Society	$10,600.00
Land, Building and Endowment Fund, collection and other expenses	996.38
General Library Fund	115.85
Carnegie (Library) Fund	253.30
Mailloux Fund	37.45
Total Expenditures	$12,002.98
Deposited to credit of their respective fund accounts	60,174.34
	$72,177.32

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONDENSED CASH STATEMENT.

EXHIBIT D.

Cash on Deposit April 30, 1905	$39,301.15	
Secretary's petty cash April 30, 1905	500.00	
	$39,801.15	
Receipts for general purposes, Ex. B	49,110.40	
Receipts for designated purposes, Ex. C	72,177.32	
		$161,088.87
Disbursements for general purposes, Ex. B	$40,767.22	
Expenditures for designated purposes, Ex. C	12,002.98	
		52,770.20
Balance on hand April 30, 1906		$108,318.67
On Deposit for designated purposes, Ex. A	92,840.33	
On deposit general, Ex. A	14,978.34	
Secretary's petty cash, Ex. A	500.00	
		$108,318.67

PROPERTY ACQUIRED DURING THE YEAR.

(Reported as directed by the Constitution.)

Office Furniture and Fixtures	$192.50
Library Books and Binding	825.00
Paintings, etc	2,300.00

Respectfully submitted for the Board of Directors,

RALPH W. POPE,
Secretary.

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